Precision Physics --
-- from LEP2 to the Terascale

Latest results and prospects

a personal selection

R.-D. Heuer, Univ. Hamburg and DESY

Cracow, 5 Jan 2008

Precision Physics --
-- from LEP2 to the Terascale

R.-D. Heuer, Univ. Hamburg and DESY

Cracow, 5 Jan 2008

Past few decades

“Discovery” of Standard Model

through synergy of

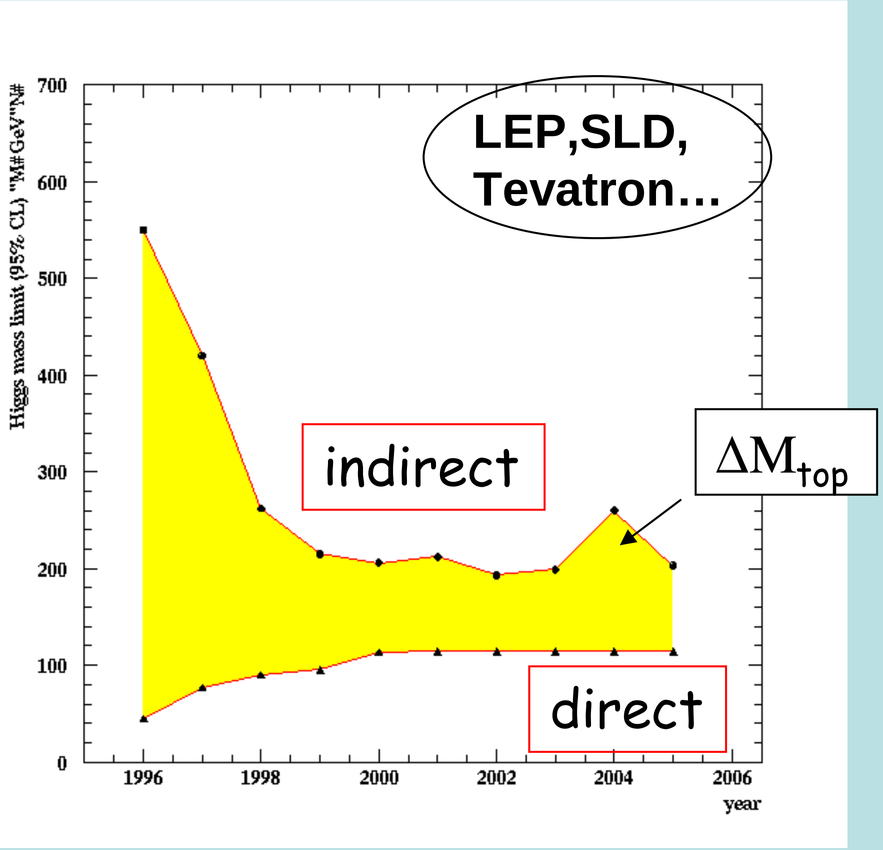
hadron - hadron colliders

lepton - hadron colliders

lepton - lepton colliders

Synergy of colliders:

Time evolution of experimental limits on the Higgs boson mass



LEP,SLD, Tevatron…

indirect

ΔM_{top}

direct

M_H between 114 and ~200 GeV

knowledge obtained only through combination of results from different accelerator types

in particular:
Lepton and Hadron Collider

Status Summer Conferences 2007

Standard Model Analysis

	Measurement	Fit
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02758 ± 0.00035	0.02768
m_Z [GeV]	91.1875 ± 0.0021	91.1875
Γ_Z [GeV]	2.4952 ± 0.0023	2.4957
σ^0_{had} [nb]	41.540 ± 0.037	41.477
R_l	20.767 ± 0.025	20.744
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21586
R_c	0.1721 ± 0.0030	0.1722
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1038
$A^{0,c}_{fb}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1481
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.398 ± 0.025	80.374
Γ_W [GeV]	2.140 ± 0.060	2.091
m_t [GeV]	170.9 ± 1.8	171.3

Fit to 17 high-Q^2 observables plus $\Delta\alpha_{had}$:

χ^2/ndof = 18.2/13 (15.1%)

Largest χ^2 contribution:
A_l(SLD) vs. A_{fb}b(LEP)

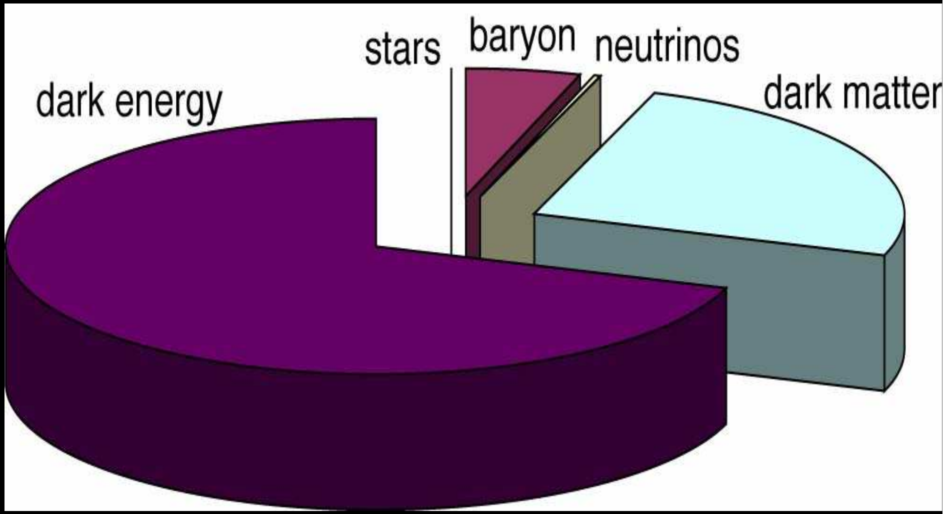
Decided in favour of leptons by M_W

Without this point, the fit is *too* good!

Afb(b) has largest pull: 2.9σ!

However.........

THE ENERGY DENSITY BUDGET



Ω_B BARYONS

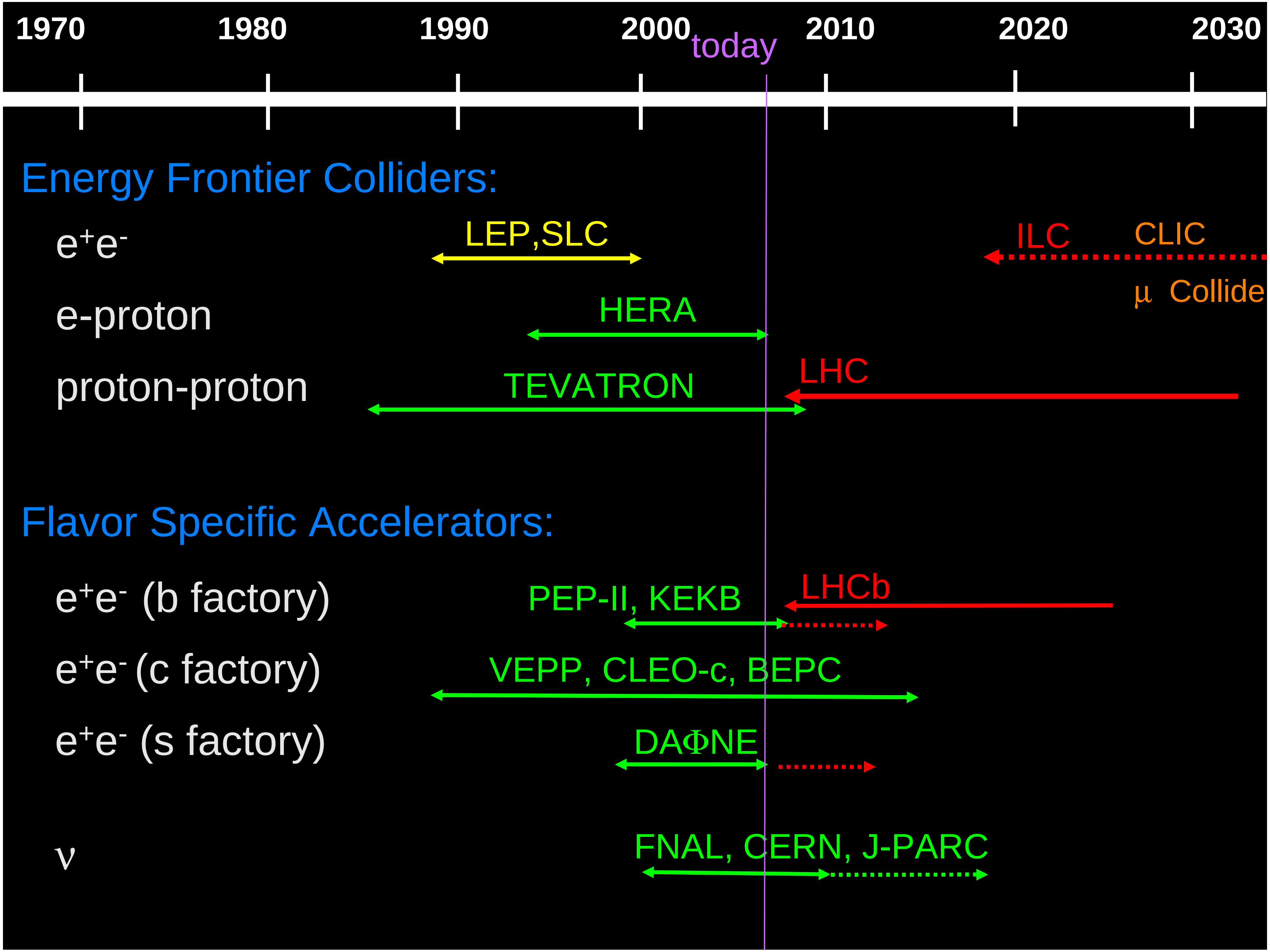
Ω_{CDM} COLD DARK MATTER

Ω_ν NEUTRINOS

Ω_{DE} DARK ENERGY

$$\Omega_{TOT} = \Omega_B + \Omega_{CDM} + \Omega_\nu + \Omega_{DE}$$

→ at the Terascale: entering the 'Dark World'



1970 1980 1990 2000 today 2010 2020 2030

Energy Frontier Colliders:

e^+e^- LEP,SLC ILC CLIC

μ Collide

e-proton HERA

proton-proton TEVATRON LHC

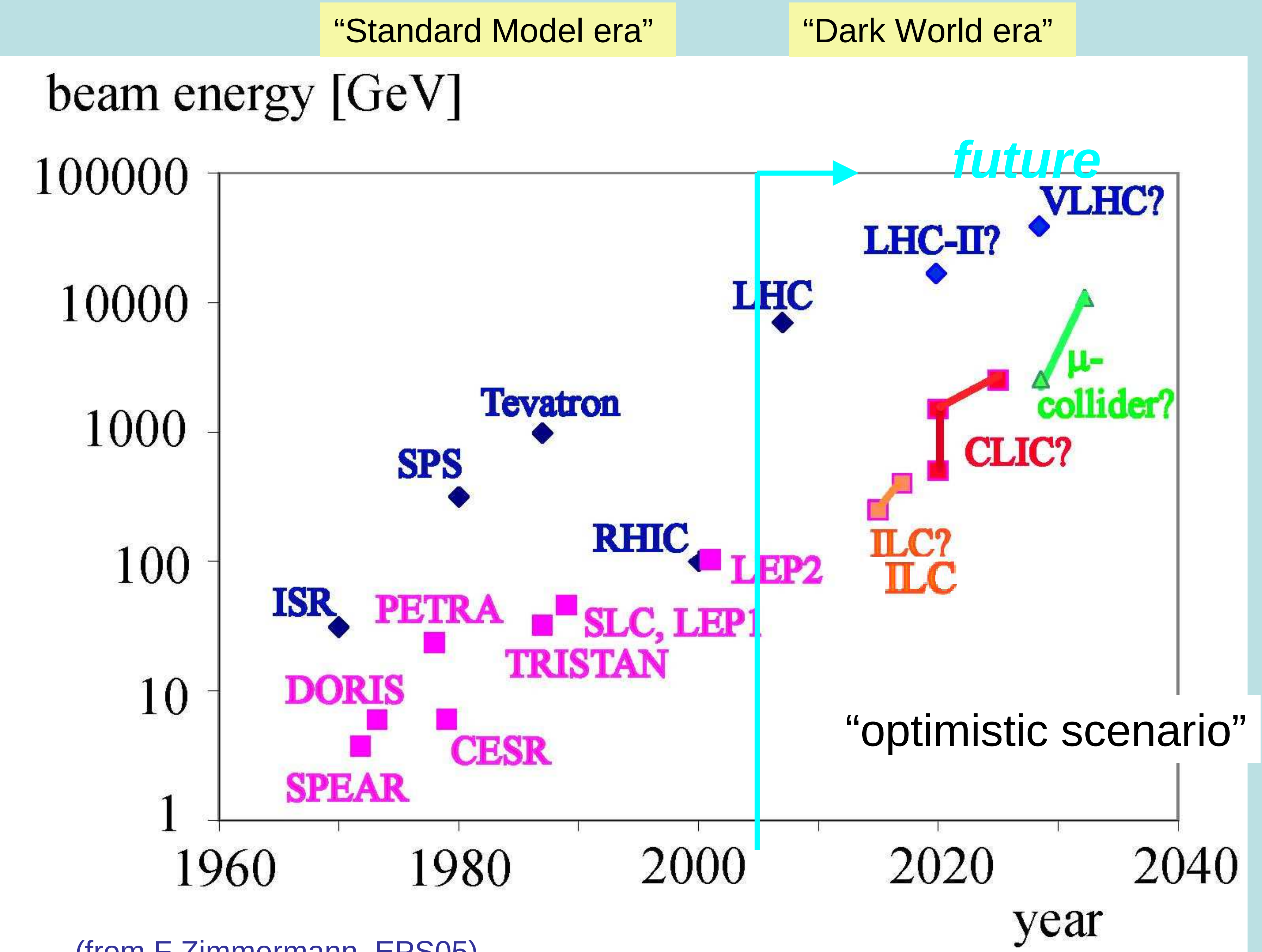
Flavor Specific Accelerators:

e^+e^- (b factory) PEP-II, KEKB LHCb

e^+e^- (c factory) VEPP, CLEO-c, BEPC

e^+e^- (s factory) DAΦNE

ν FNAL, CERN, J-PARC



"Standard Model era"

"Dark World era"

future

"optimistic scenario"

(from F.Zimmermann, EPS05)

High Energy Colliders: Tevatron and HERA

Tevatron Run II
$\int L dt = 3\ fb^{-1}$ /exp

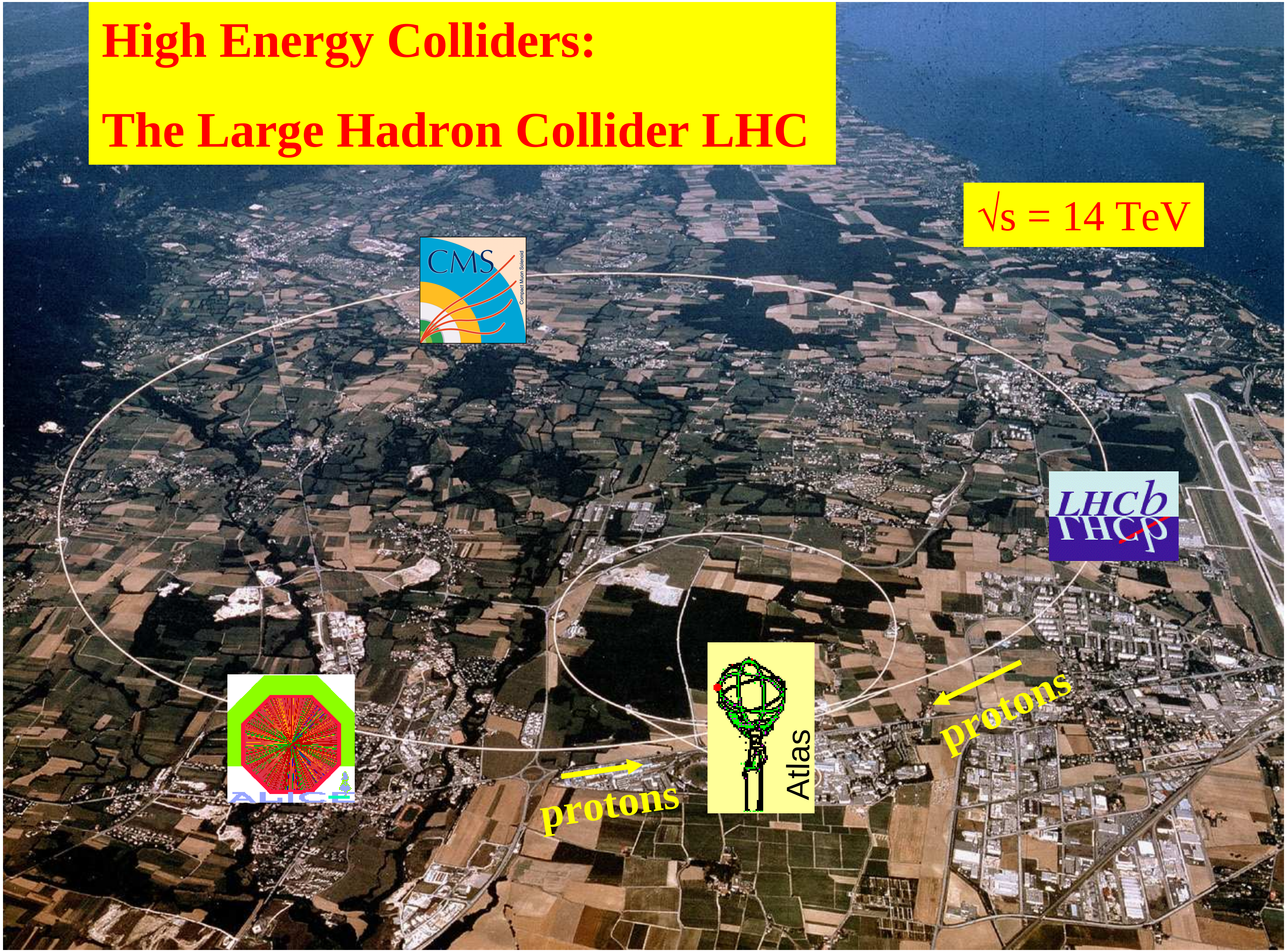
HERA Run I+II
$\int L dt = 0.5\ fb^{-1}$ /exp

$\sqrt{s}$=1.96 TeV

$\sqrt{s}$=0.32 TeV

High Energy Colliders:

The Large Hadron Collider LHC



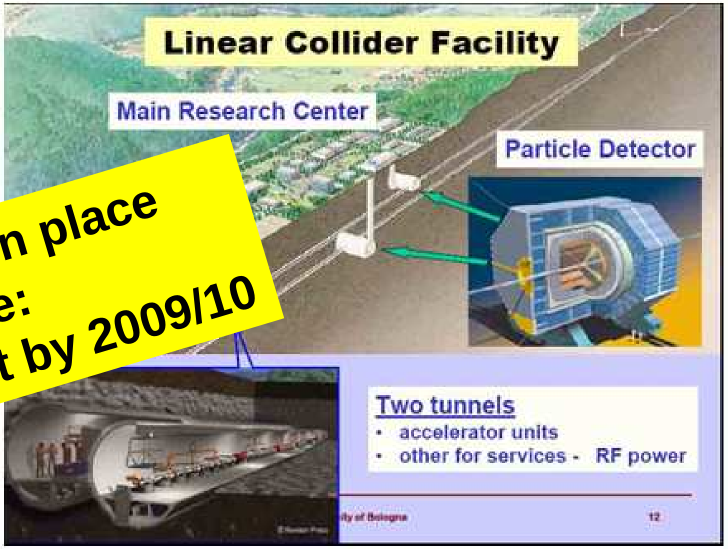
$\sqrt{s} = 14$ TeV

High Energy Colliders: ILC (E_{cm} up to ~ 1TeV)

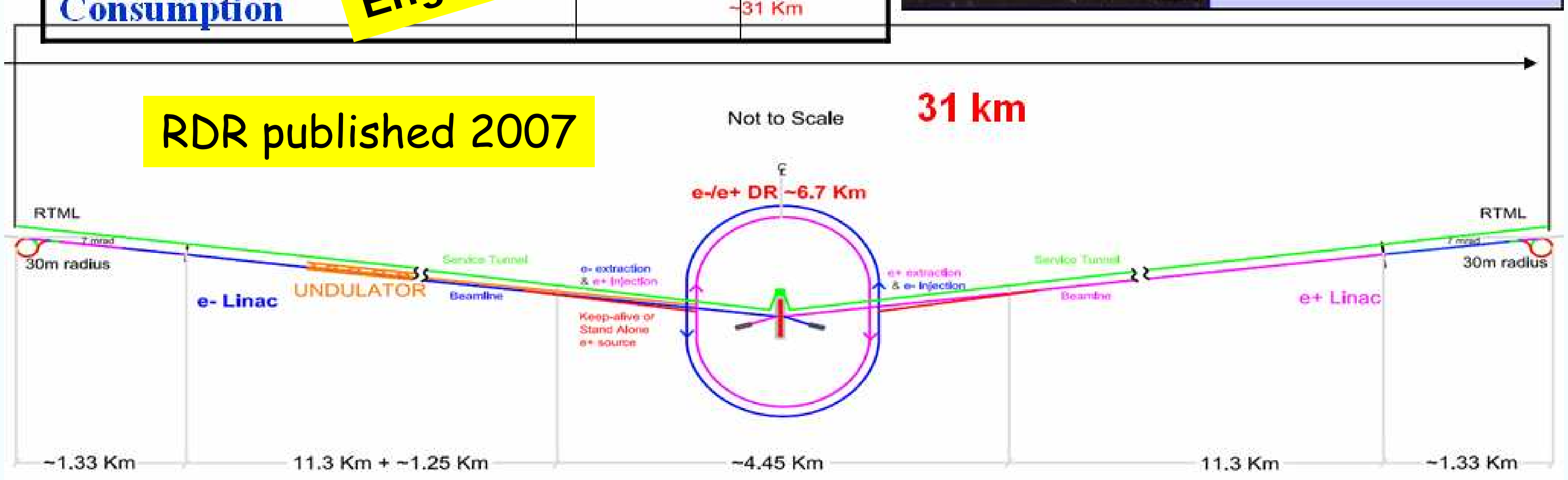
ILC @ 500 GeV

ILC web site: http://www.linearcollider.org/cms/

Max. Center-of-mass energy	500	GeV
Peak Luminosity	$\sim 2\times10^{34}$	$cm^{-2}s^{-1}$
Beam Current	9.0	mA
Repetition rate	5	Hz
Average accelerating gradient	[illegible]	[illegible]
Beam pulse length	[illegible]	[illegible]
Total Site Length	[illegible]	[illegible]
Total AC Power Consumption	~230	MW



Global Design Effort (GDE) in place
Technically driven schedule:
Engineering Design Report by 2009/10



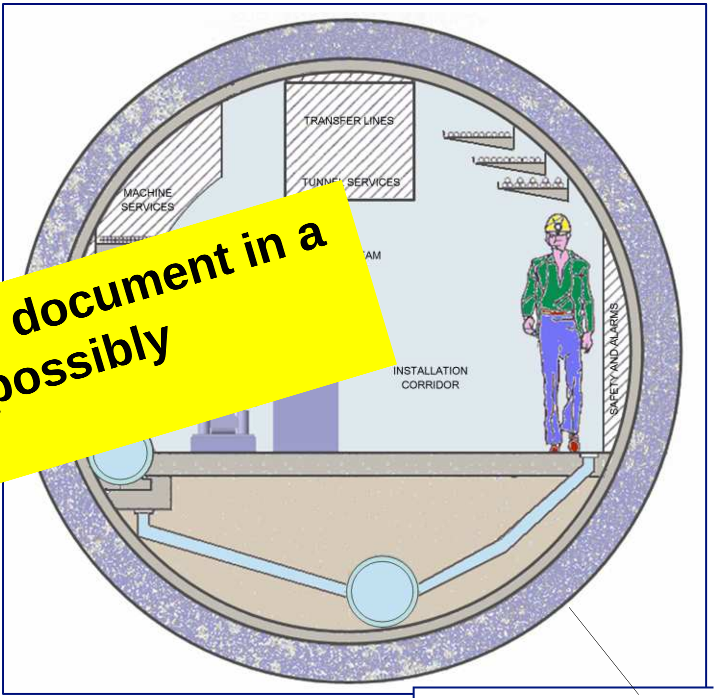
RDR published 2007

High Energy Colliders: CLIC (E$_{cm}$ up to ~ 3TeV)

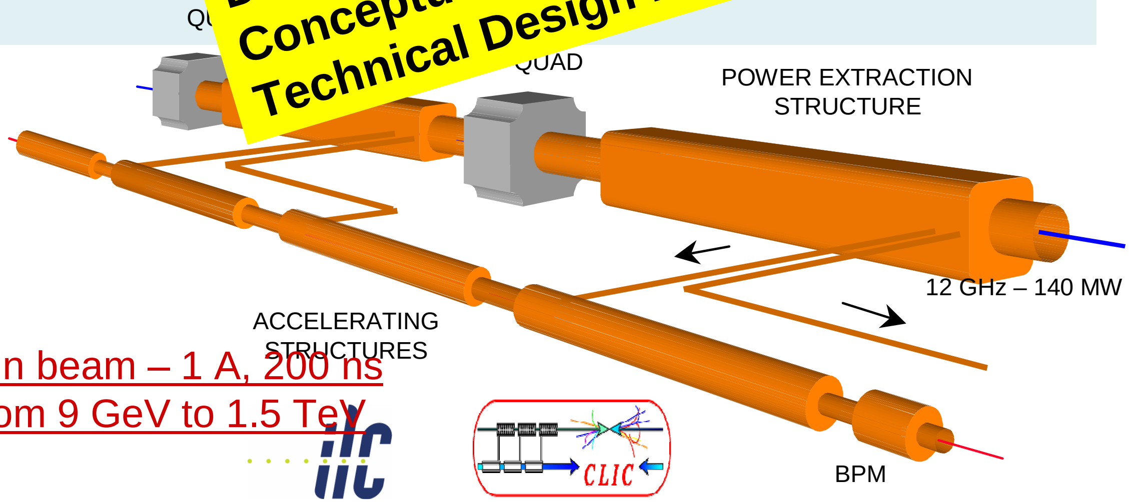
- **High acceleration gradient: ~ 100 MV/m**
  - **"Compact" collider – total length < 50 km at 3 TeV**
  - **Normal conducting acceleration structures at high frequency**
- **Novel Two-Beam Acceleration Scheme**
  - **Cost effective, reliable, efficient**
  - **Simple tunnel, no active**
  - **Modular, easy e**
    stages

Demonstrate all key feasibility issues and document in a Conceptual Design Report by 2010 and possibly Technical Design Report by 2015

CLIC TUNNEL
CROSS-SECTION



4.5 m diameter

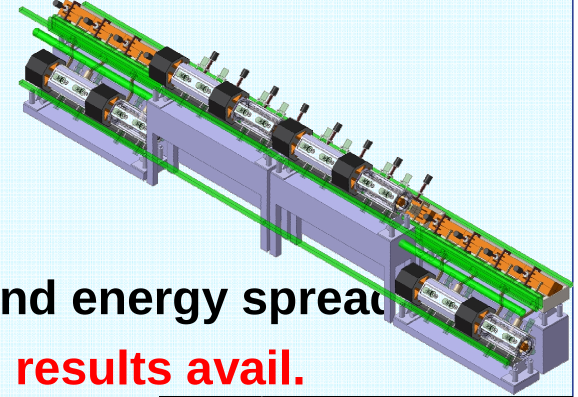


Drive beam - 95 A, 300 ns
from 2.4 GeV to 240 MeV

Main beam – 1 A, 200 ns
from 9 GeV to 1.5 TeV

THE COMPACT LINEAR COLLIDER (CLIC) STUDY

Aim: develop technology to extend e-/e+ linear colliders into the Multi-TeV energy range:



http://clic-study.web.cern.ch/CLIC-Study/

✓ E_{CM} energy range from ILC to LHC maximum reach and beyond =>E_{CM} = 0.5- 3 TeV

✓ L > few 10^{34} cm^{-2} with acceptable background and energy spread

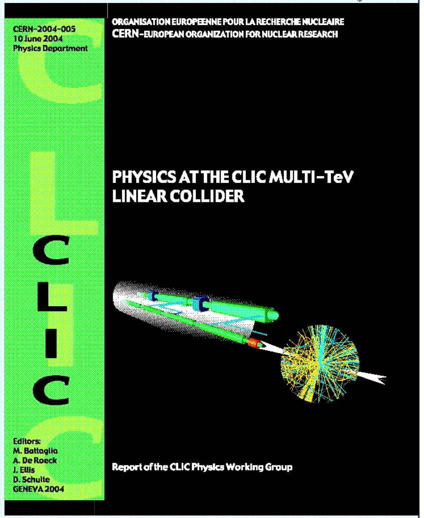
⇒ E_{CM} and L to be reviewed when LHC physics results avail.

✓ Affordable cost and power consumption

Physics motivation:

http://clicphysics.web.cern.ch/CLICphysics/

"Physics at the CLIC Multi-TeV Linear Collider:
by the CLIC Physics Working Group:CERN 2004-5



CERN-2004-005
10 June 2004
Physics Department

ORGANISATION EUROPEENNE POUR LA RECHERCHE NUCLEAIRE
CERN-EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CLIC

PHYSICS AT THE CLIC MULTI-TeV LINEAR COLLIDER

Editors:
M. Battaglia
A. De Roeck
J. Ellis
D. Schulte
GENEVA 2004

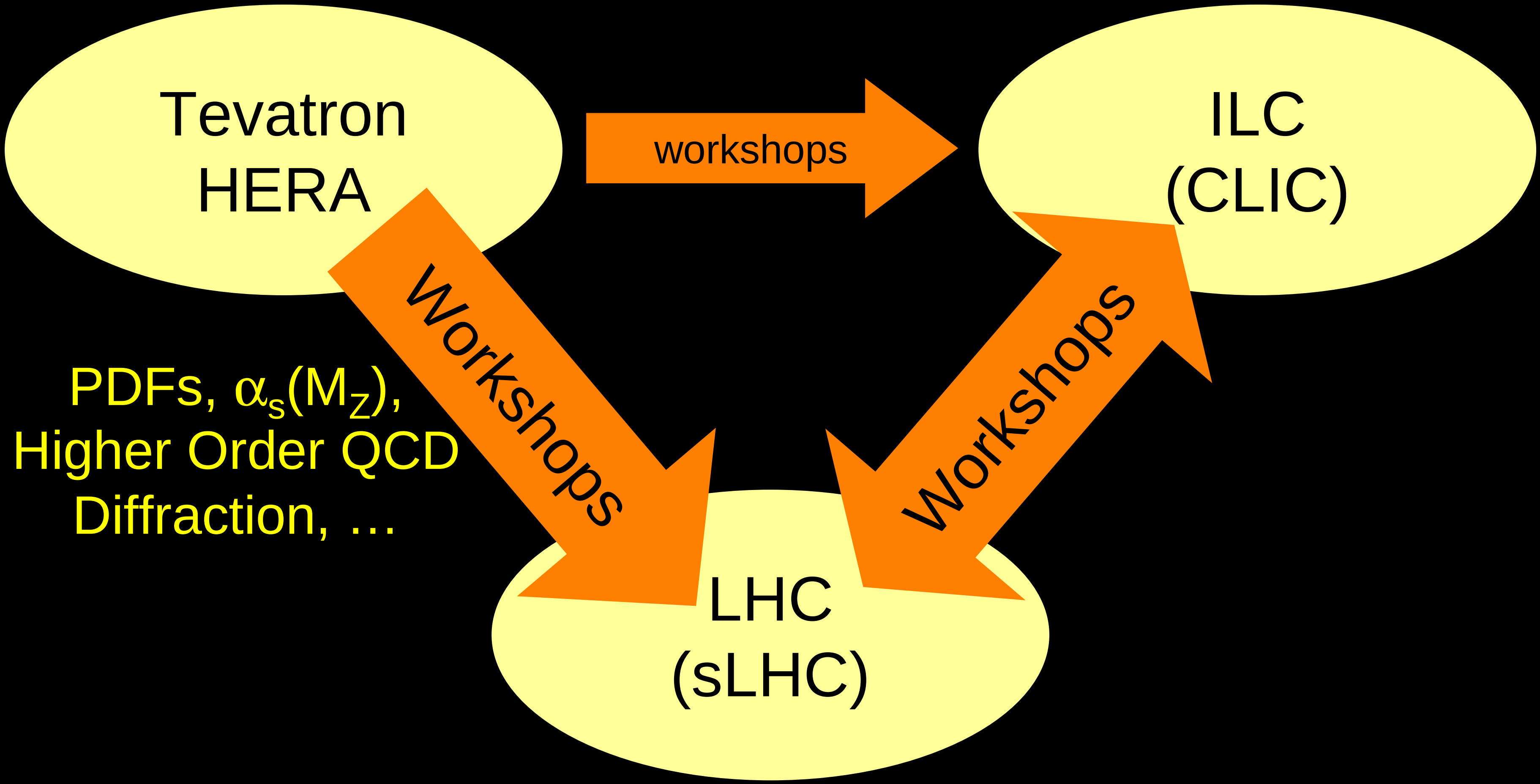
Report of the CLIC Physics Working Group

Present goal:

Demonstrate all key feasibility issues and document in a Conceptual Design Report by 2010 and possibly Technical Design Report by 2015

Synergy: Energy Frontier Accelerators

To be ready for the next accelerators
a lot of activities around the world!



Tevatron
HERA

workshops

ILC
(CLIC)

Workshops

Workshops

LHC
(sLHC)

PDFs, $\alpha_s(M_Z)$,
Higher Order QCD
Diffraction, …

Precision Physics:
requires precise detectors

and precise calculations

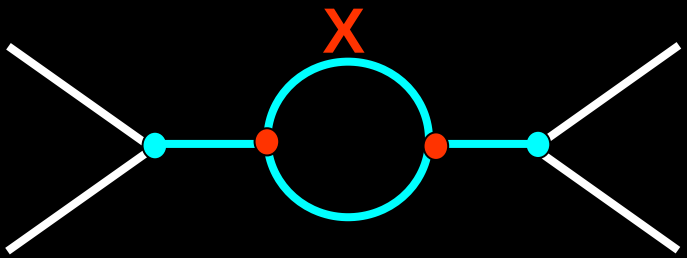
Precision Observations

Comparison of electroweak precision observables with theory

EW Precision data:
M_W, $\sin^2\theta_{\mathrm{eff}}$, α_μ, …

Theory:
SM, MSSM, ….

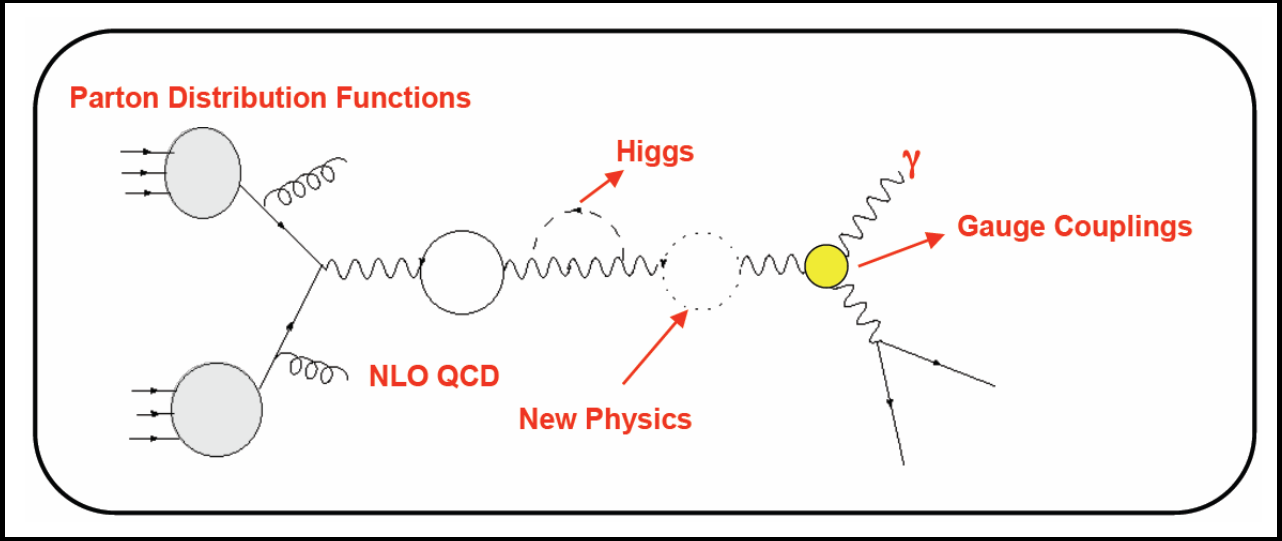
Test of theory at quantum level: sensitivity to loop corrections



Accurate measurements and theoretical predictions needed:
Which model fits better?
Does the prediction of a model contradict the experimental data?

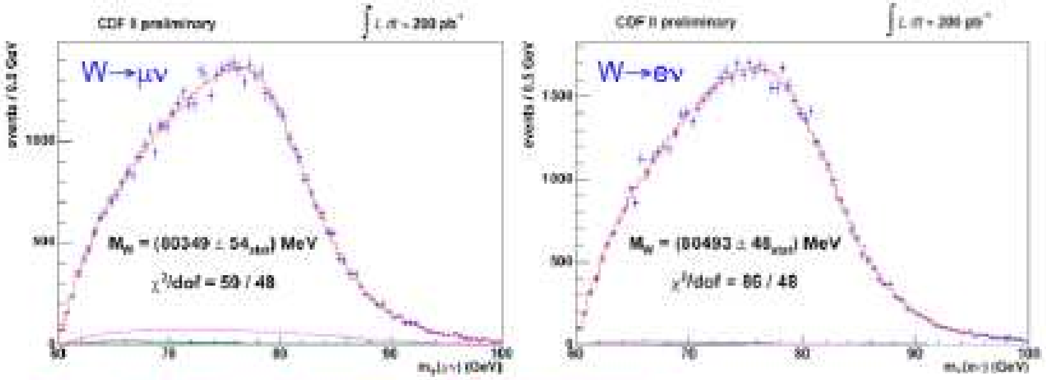
Precision Electroweak Measurements

W and Z Physics at Tevatron



W mass
W width (world average: 60 → 47 MeV)
Z Boson invisible width ~10% meas.
Tri-linear gauge bosons
    Best limits to date on WWZ coupling
W Charge asymmetry
Z rapidity
….

W Mass and Width from CDF



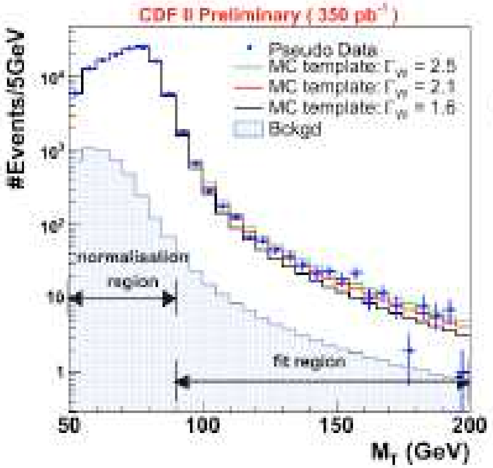
- m_W = 80413 ± 34(stat) ± 34(syst) MeV
- Major systematics:
  - lepton p_T scale and resolution, QED, PDF

CDF chooses to treat CTEQ6 er

[redacted]

[redacted]

W Mass and Width from CDF



- Major systematics:
  - lepton p_T resolution ~30 MeV
  - recoil model ~50 MeV
  - backgrounds ~30 MeV
  - uncorrelated between electron and muon channels

Γ_W = 2032 ± 71 (stat + syst) MeV (350 pb-1)

c.f. indirect measurement from cross sections: $R = \dfrac{\sigma \cdot \mathrm{BR}\,(W \to l\nu)}{\sigma \cdot \mathrm{BR}\,(Z \to ll)}$

Γ_W = 2092 ± 42 MeV (stat + syst) MeV (72 pb-1)

W-Physics at LEP

expectation in
„Physics at LEP (1986)"

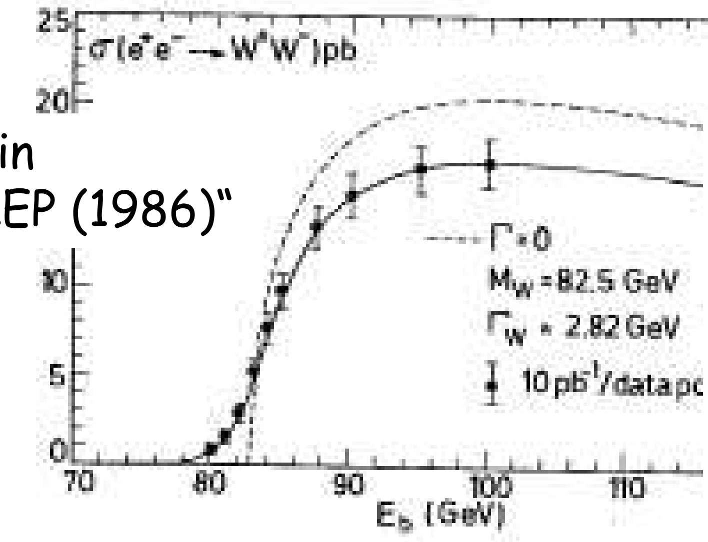
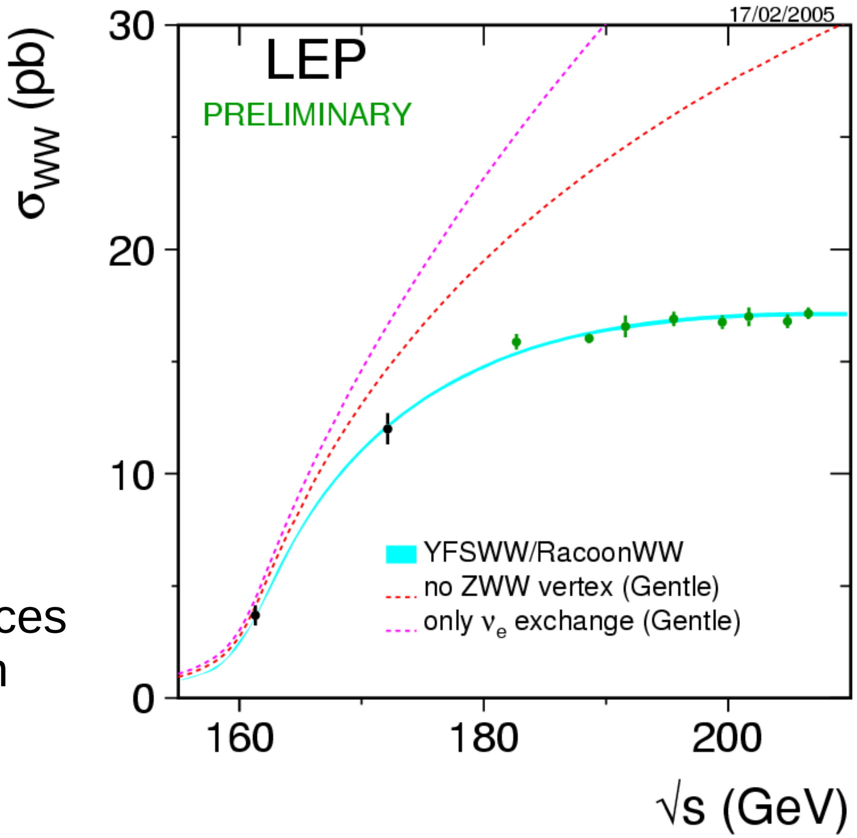
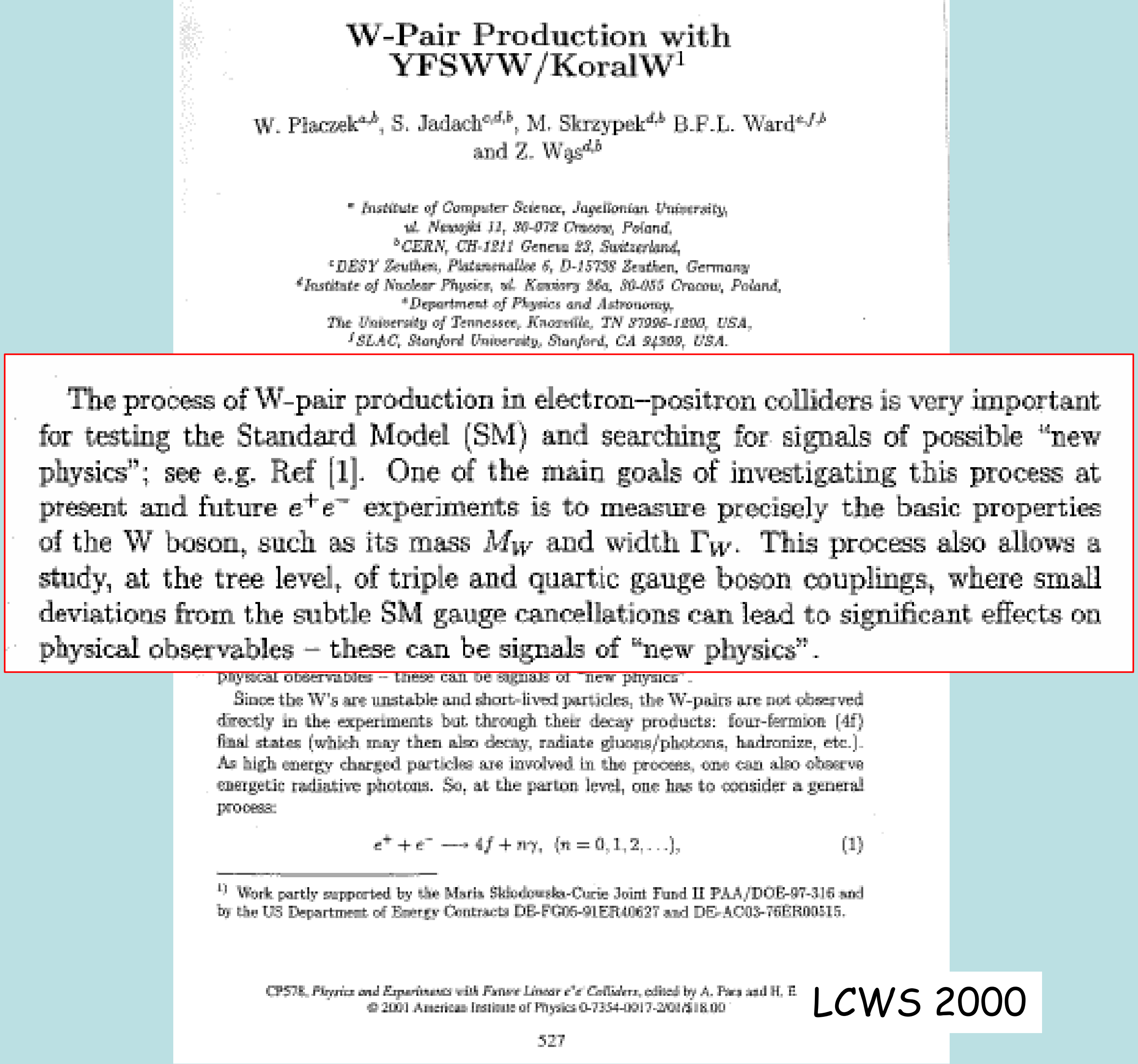


Fig 26: Statistical errors and running time distribution to ob

ΔM_W = 138 MeV

Verification of triple gauge vertices
from $e^+e^- \rightarrow W^+W^-$ cross section





W-Pair Production with YFSWW/KoralW[1]

W. Płaczek[a,b], S. Jadach[c,d,b], M. Skrzypek[d,b] B.F.L. Ward[e,f,b]
and Z. Wąs[d,b]

[a] *Institute of Computer Science, Jagellonian University,*
ul. Nawojki 11, 30-072 Cracow, Poland,
[b] *CERN, CH-1211 Geneva 23, Switzerland,*
[c] *DESY Zeuthen, Platanenallee 6, D-15738 Zeuthen, Germany*
[d] *Institute of Nuclear Physics, ul. Kawiory 26a, 30-055 Cracow, Poland,*
[e] *Department of Physics and Astronomy,*
The University of Tennessee, Knoxville, TN 37996-1200, USA,
[f] *SLAC, Stanford University, Stanford, CA 94309, USA.*

The process of W-pair production in electron–positron colliders is very important for testing the Standard Model (SM) and searching for signals of possible "new physics"; see e.g. Ref [1]. One of the main goals of investigating this process at present and future e^+e^- experiments is to measure precisely the basic properties of the W boson, such as its mass M_W and width Γ_W. This process also allows a study, at the tree level, of triple and quartic gauge boson couplings, where small deviations from the subtle SM gauge cancellations can lead to significant effects on physical observables – these can be signals of "new physics".

physical observables – these can be signals of "new physics".

Since the W's are unstable and short-lived particles, the W-pairs are not observed directly in the experiments but through their decay products: four-fermion (4f) final states (which may then also decay, radiate gluons/photons, hadronize, etc.). As high energy charged particles are involved in the process, one can also observe energetic radiative photons. So, at the parton level, one has to consider a general process:

$$e^+ + e^- \longrightarrow 4f + n\gamma, \quad (n = 0, 1, 2, \ldots), \tag{1}$$

---

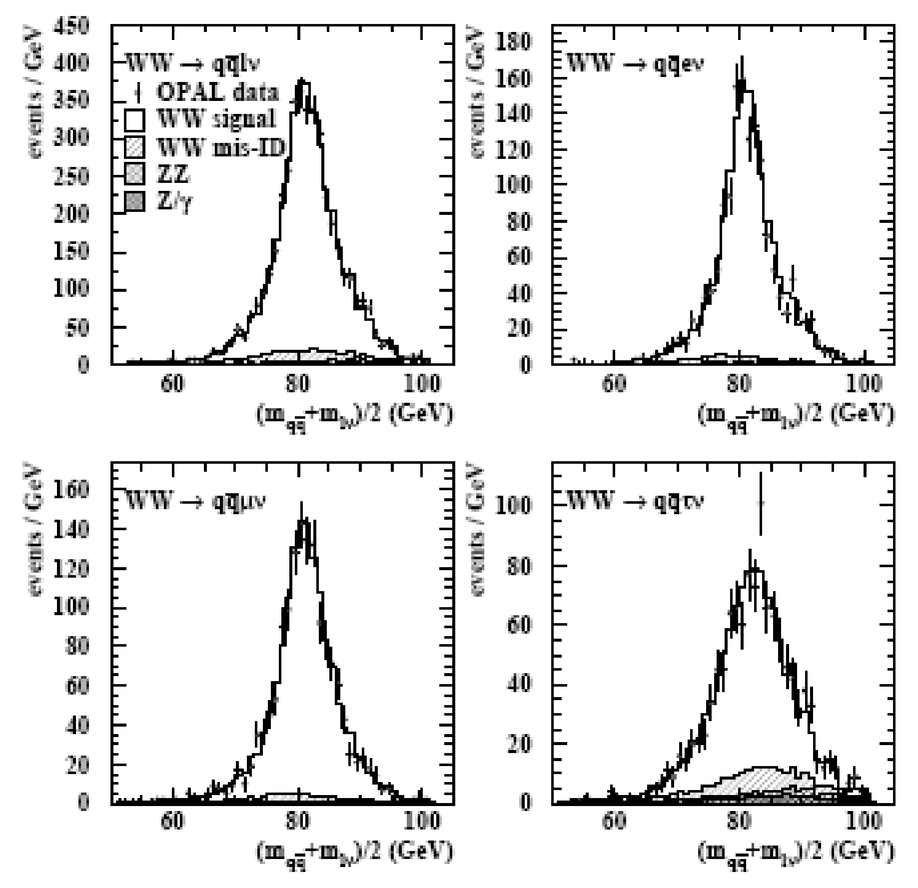
[1] Work partly supported by the Maria Sklodowska-Curie Joint Fund II PAA/DOE-97-316 and by the US Department of Energy Contracts DE-FG05-91ER40627 and DE-AC03-76ER00515.

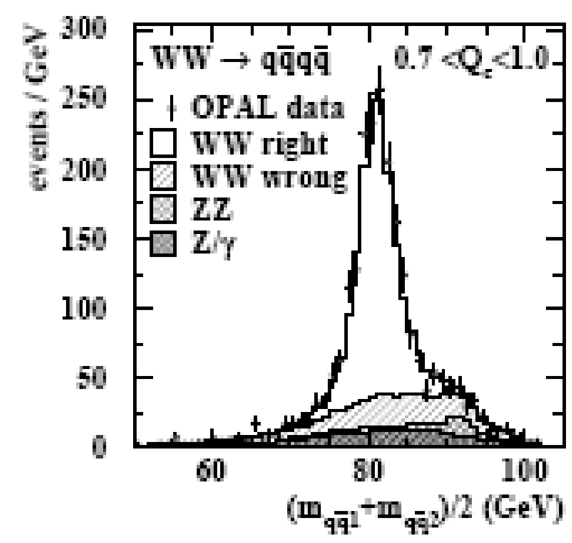
CP578, *Physics and Experiments with Future Linear e⁺e⁻ Colliders*, edited by A. Para and H. E.

LCWS 2000

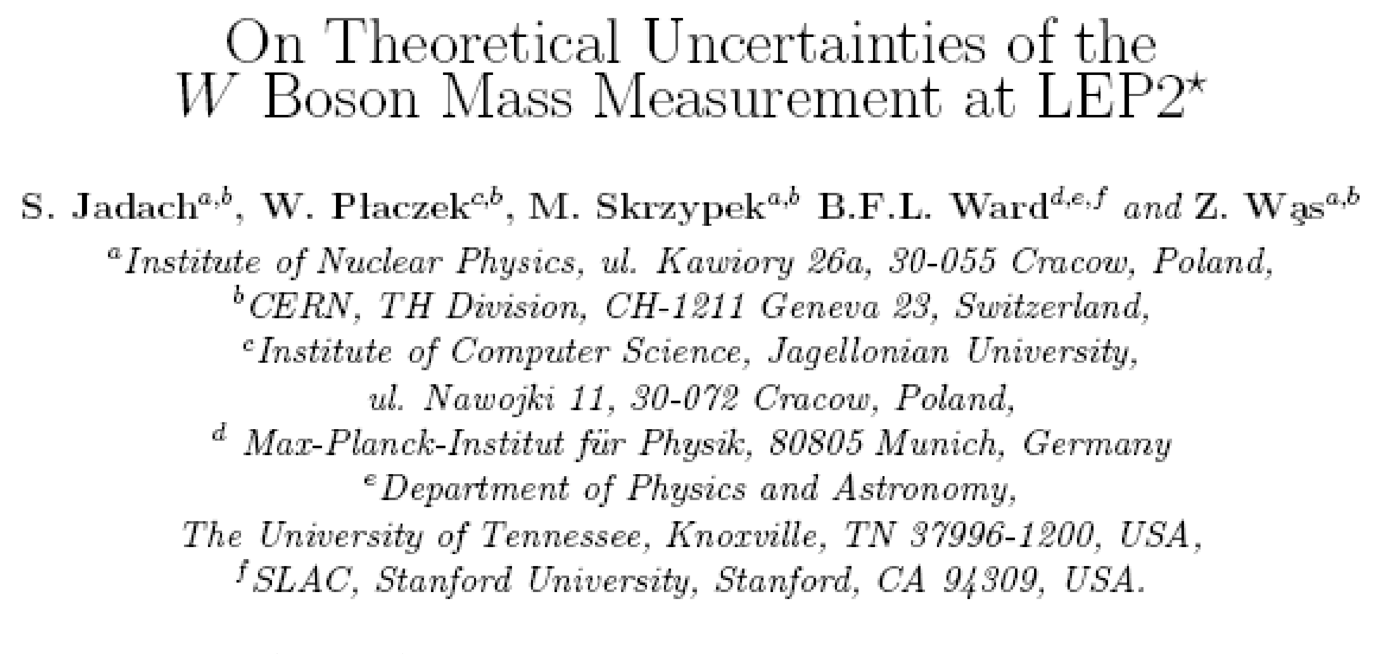
M_W at LEP

ex: OPAL





M_W (LEP combined) 80.376 ± 0.033 GeV (prel.)



On Theoretical Uncertainties of the W Boson Mass Measurement at LEP2[⋆]

S. Jadach[a,b], W. Płaczek[c,b], M. Skrzypek[a,b] B.F.L. Ward[d,e,f] *and* Z. Wąs[a,b]

[a]*Institute of Nuclear Physics, ul. Kawiory 26a, 30-055 Cracow, Poland,*
[b]*CERN, TH Division, CH-1211 Geneva 23, Switzerland,*
[c]*Institute of Computer Science, Jagellonian University,*
ul. Nawojki 11, 30-072 Cracow, Poland,
[d] *Max-Planck-Institut für Physik, 80805 Munich, Germany*
[e]*Department of Physics and Astronomy,*
The University of Tennessee, Knoxville, TN 37996-1200, USA,
[f]*SLAC, Stanford University, Stanford, CA 94309, USA.*

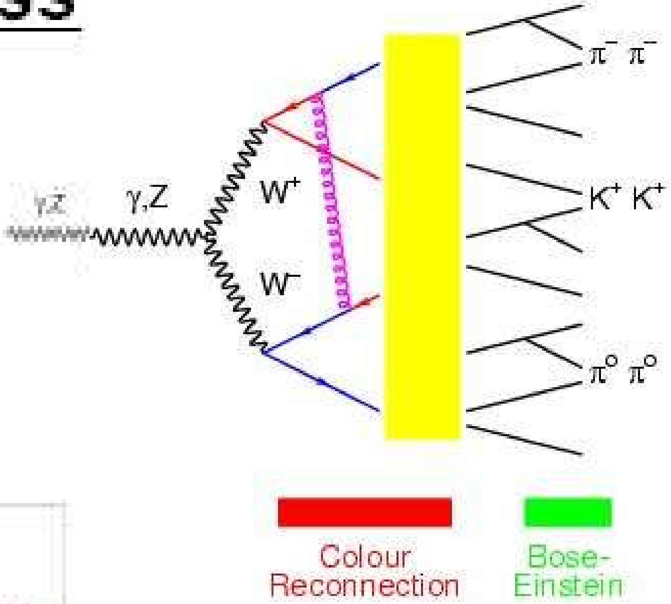
Phys.Lett.B533,75 (2002)

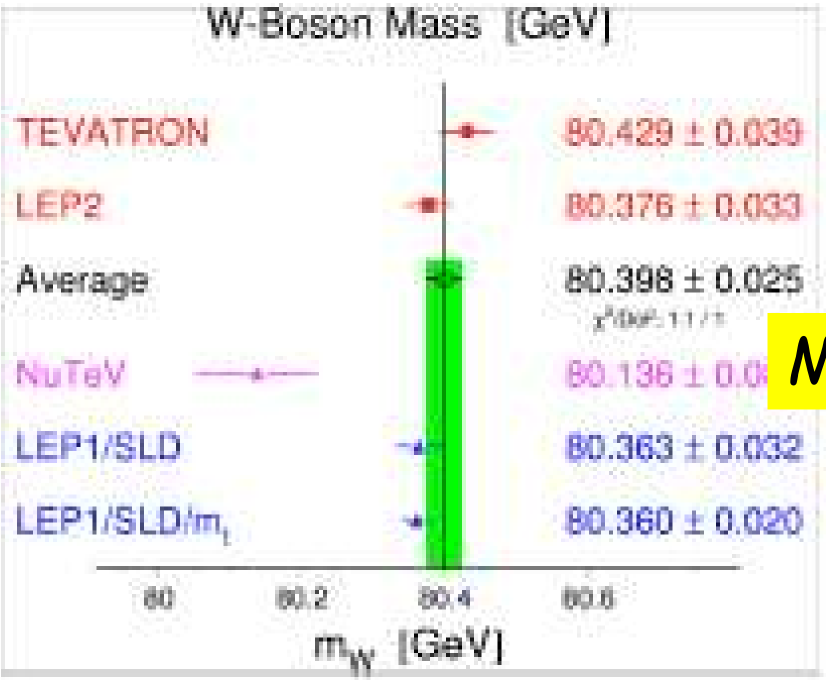
We discuss theoretical uncertaint
at LEP2 energies, reconstructed wit
event generators KoralW and YFS
with these programs, and the exist
that the theoretical uncertainty of t
reconstructed at LEP2 with the hel
certain idealized event selections and
exercises can be (should be) repeated
LEP2 measurements, using KoralW

To be submitt

W Mass

- Final LEP2 M_W awaits:
  - final combination of colour reconnection limits
  - final M_W combination

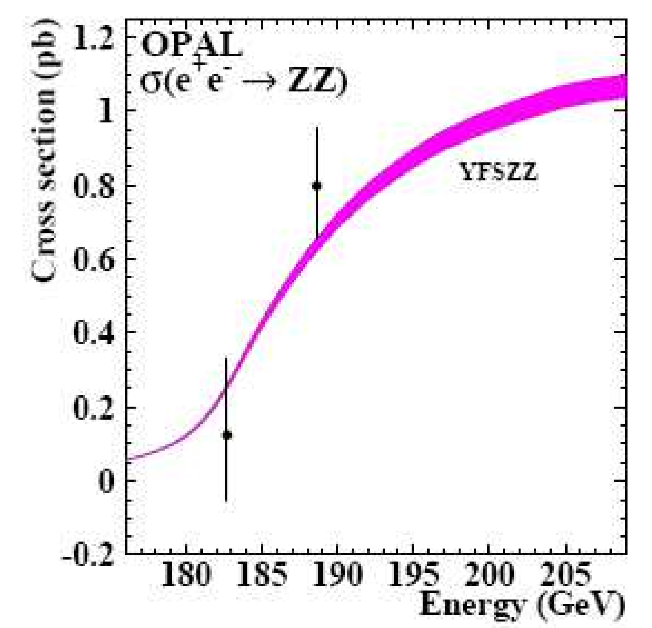




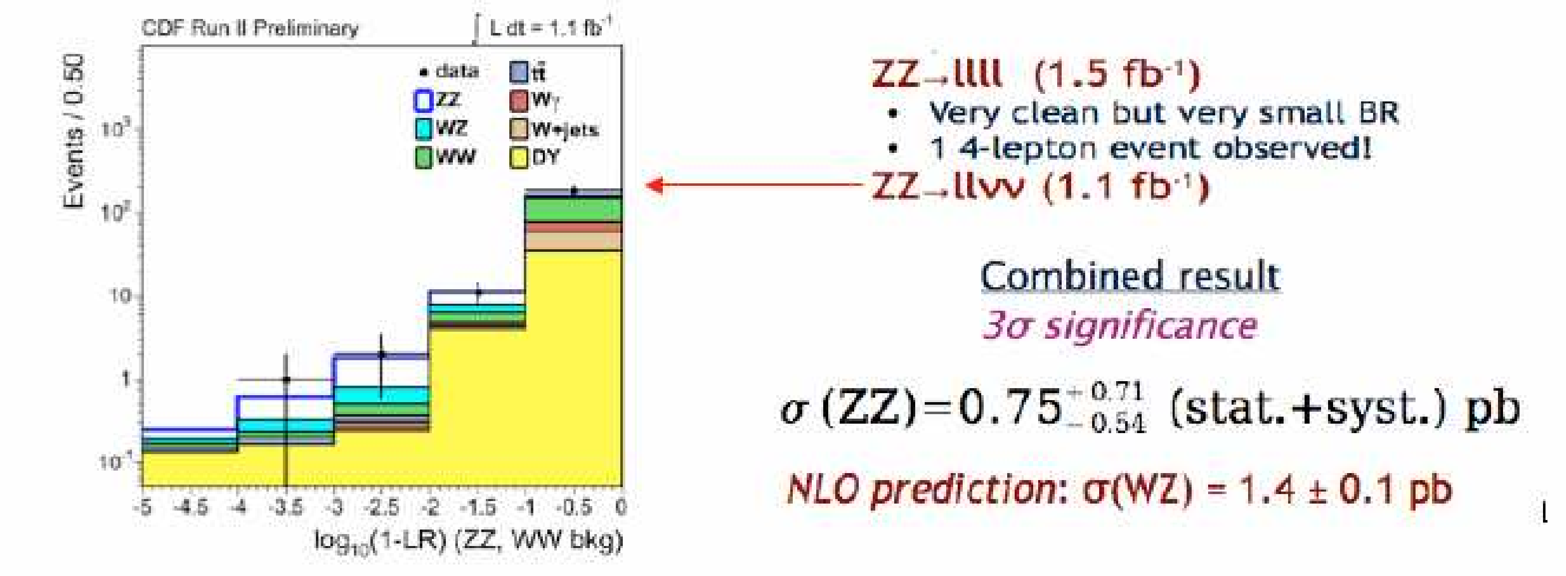
$\Delta m_W = 25$ MeV

M_W 80.398 ± 0.025 GeV

ZZ final states at LEP (ex. OPAL)
Comparison to YFSZZ



WW,ZZ final states not yet observed at the Tevatron
(first WZ events observed early 2007)



ZZ→llll (1.5 fb⁻¹)

- Very clean but very small BR
- 1 4-lepton event observed!

ZZ→llνν (1.1 fb⁻¹)

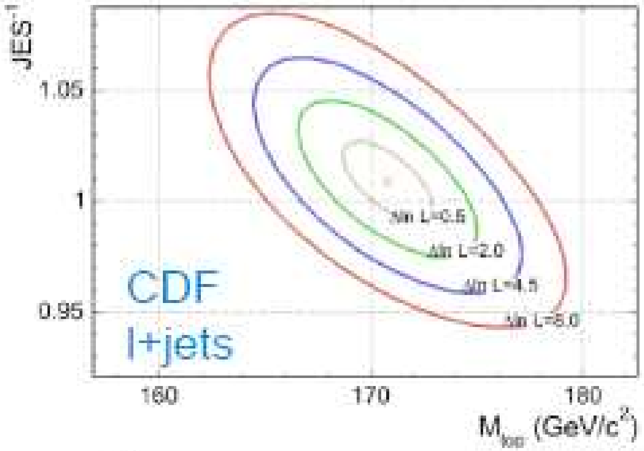
Combined result
3σ significance

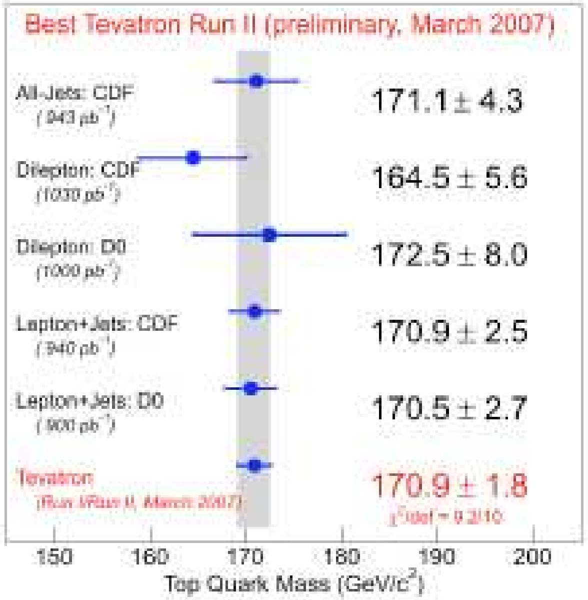
$$\sigma(\mathrm{ZZ}) = 0.75^{+0.71}_{-0.54} \text{ (stat.+syst.) pb}$$

NLO prediction: σ(WZ) = 1.4 ± 0.1 pb

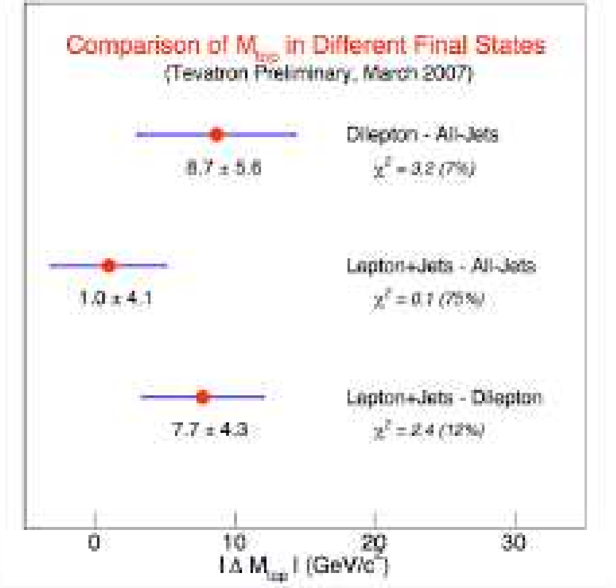
Top Mass Measurement

- Dominant systematics
    - ISR
    - FSR
    - PDFs
    - b-jet energy scale
    - b fragmentation



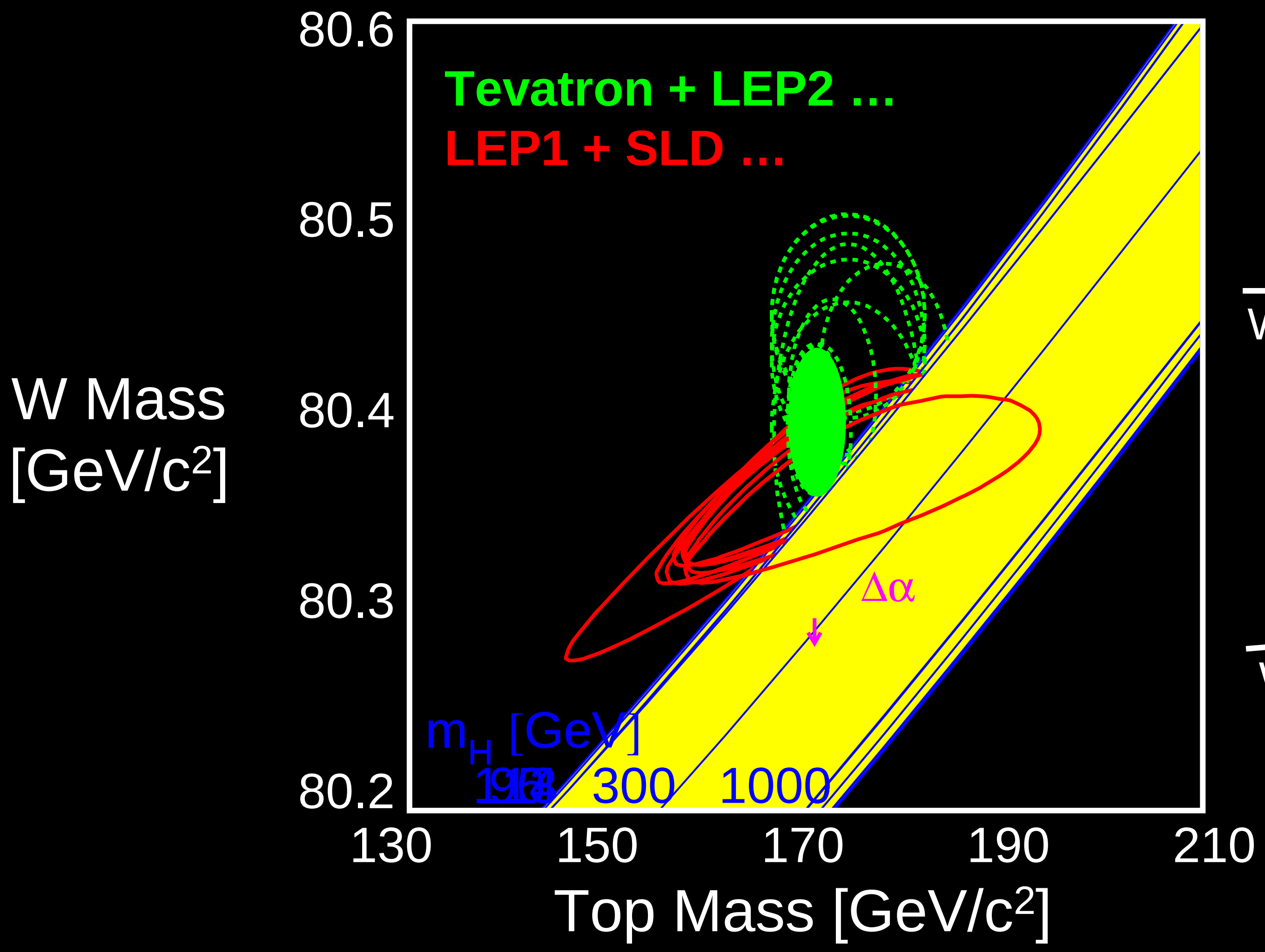


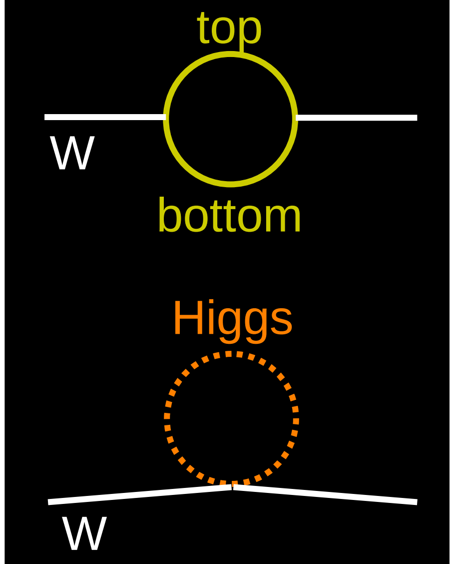
$\Delta m_{top} / m_{top}$~1%



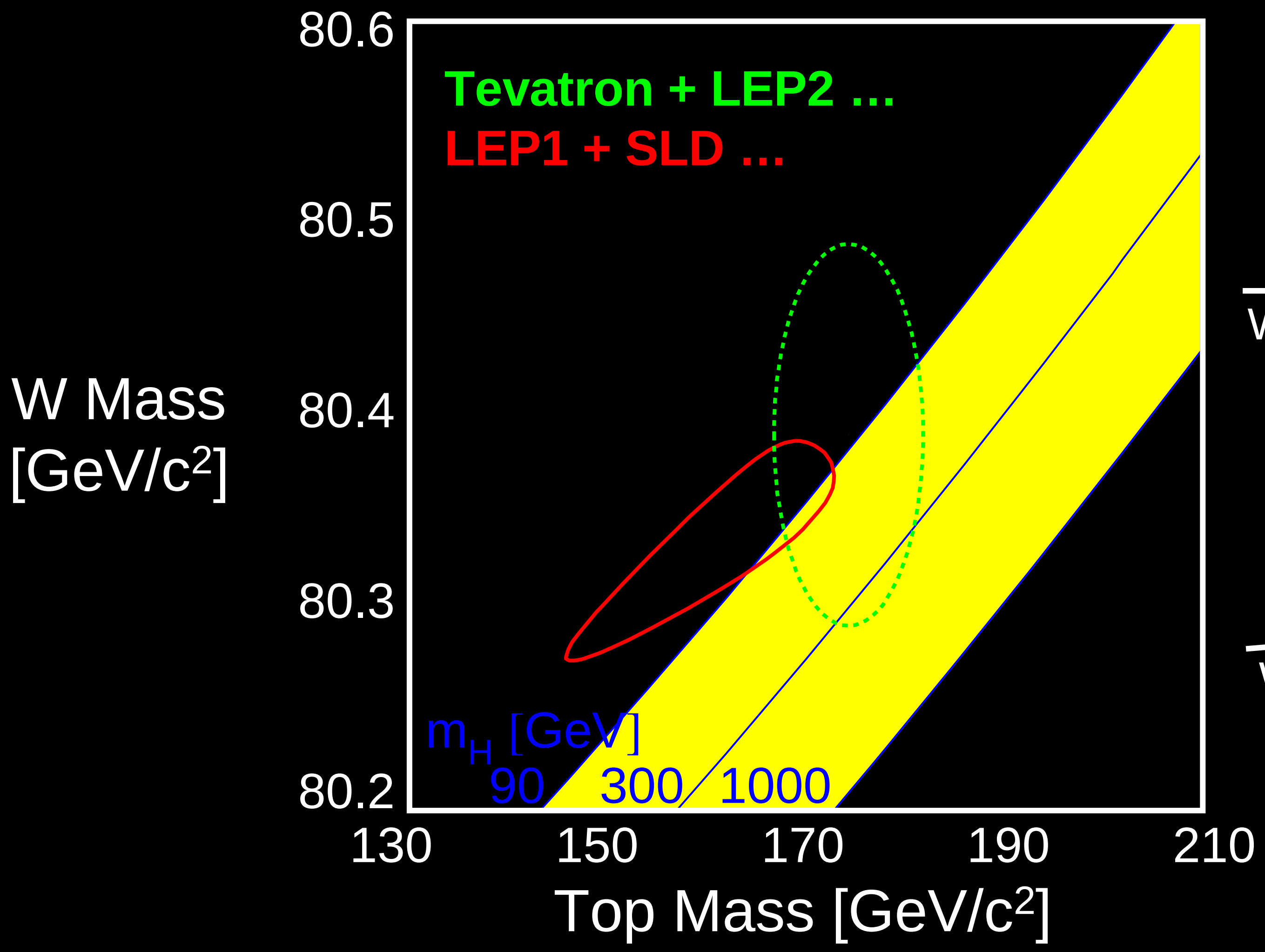
- Is m_{top} in Monte Carlos used by experiments the same as m_{top} (pole) used in the EW fits?
    - e.g., colour reconnection effects?

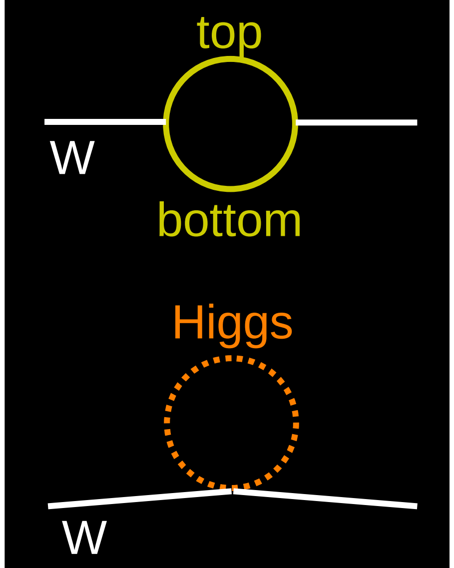
W and Top Mass: from 1998 to 2007



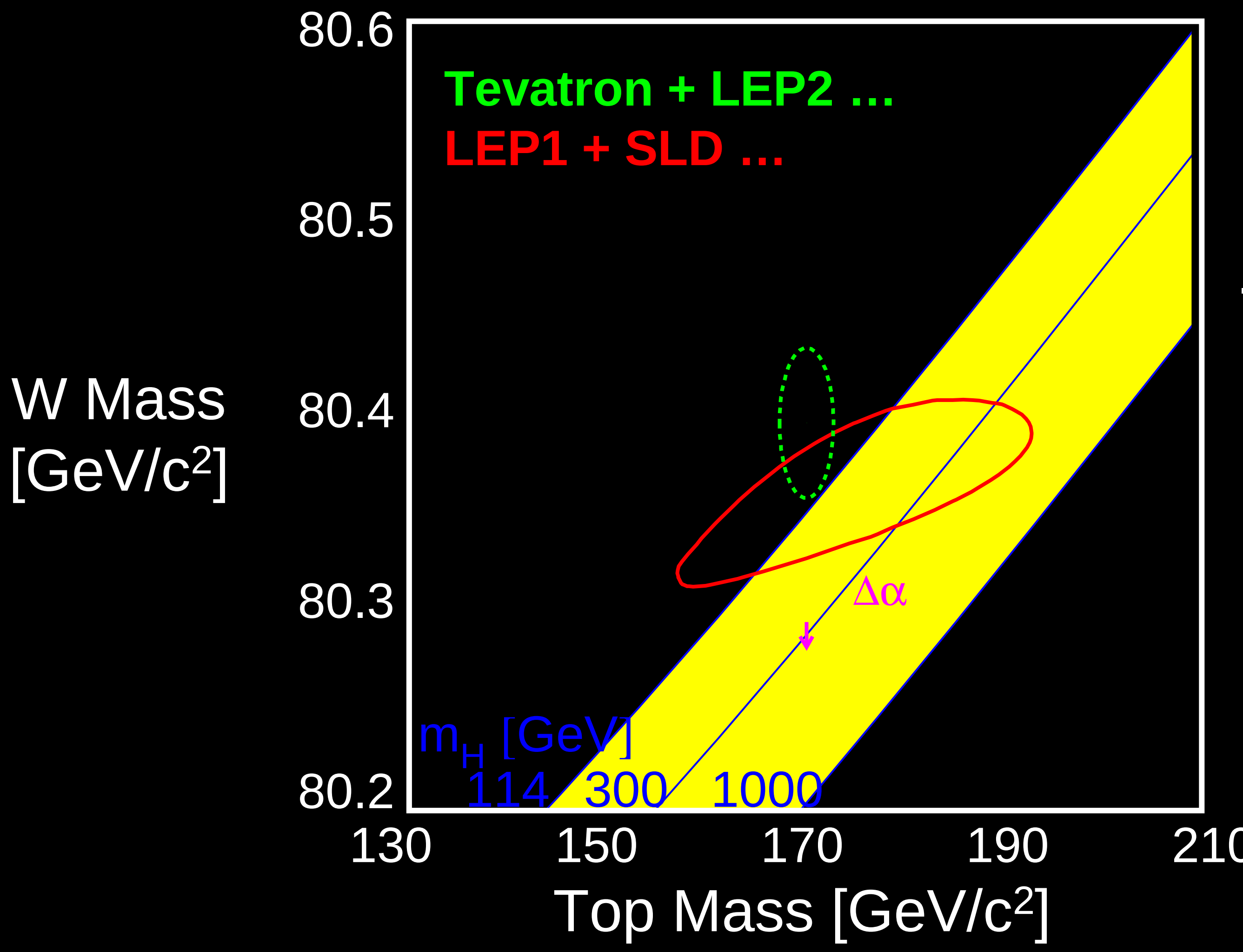


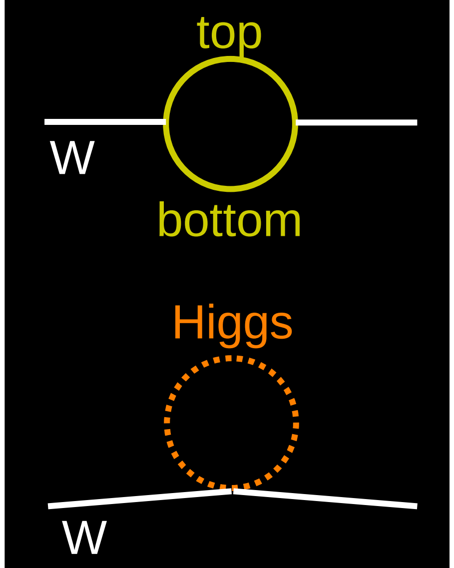
W and Top Mass: 1998





W and Top Mass: 2007

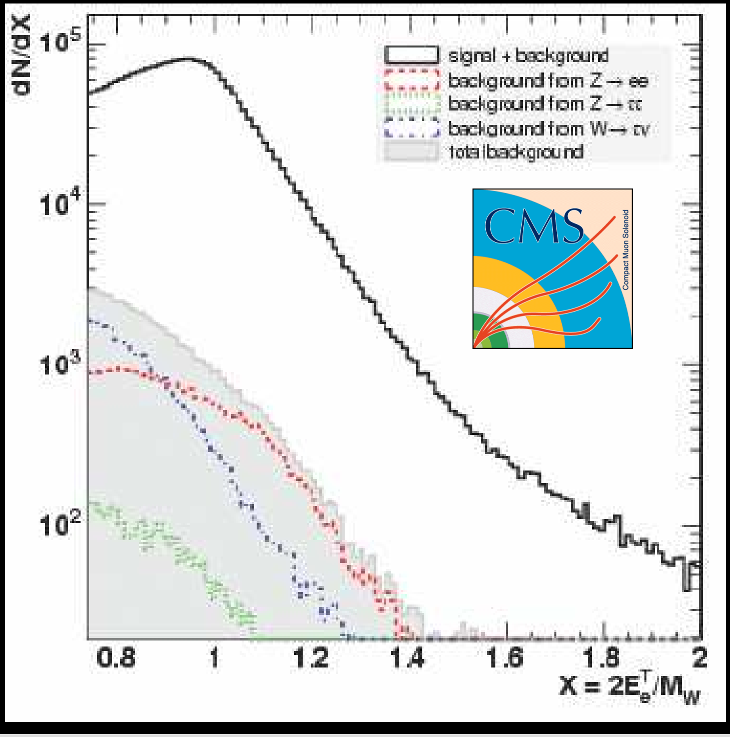


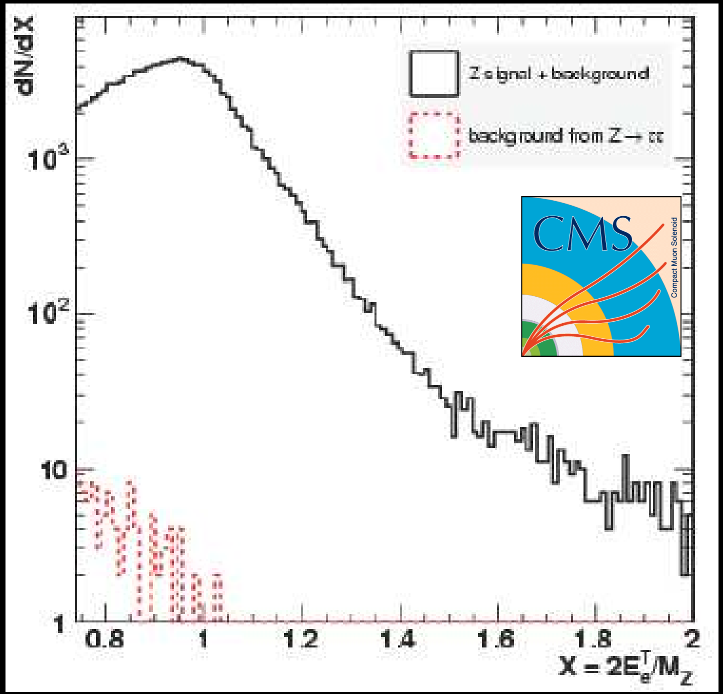


Higgs mass < ~144 GeV at 95%CL (without new LP07 M_{top})

W/Z Physics at the LHC

- **Very clean selection of W and Z boson possible e.g. CMS study of W→ eν and Z → ee**





- **Recall rates (initial phase 10^{33}/cm^2/s):**

≈ 200 W/s → ≈ 20 W→ eν /s

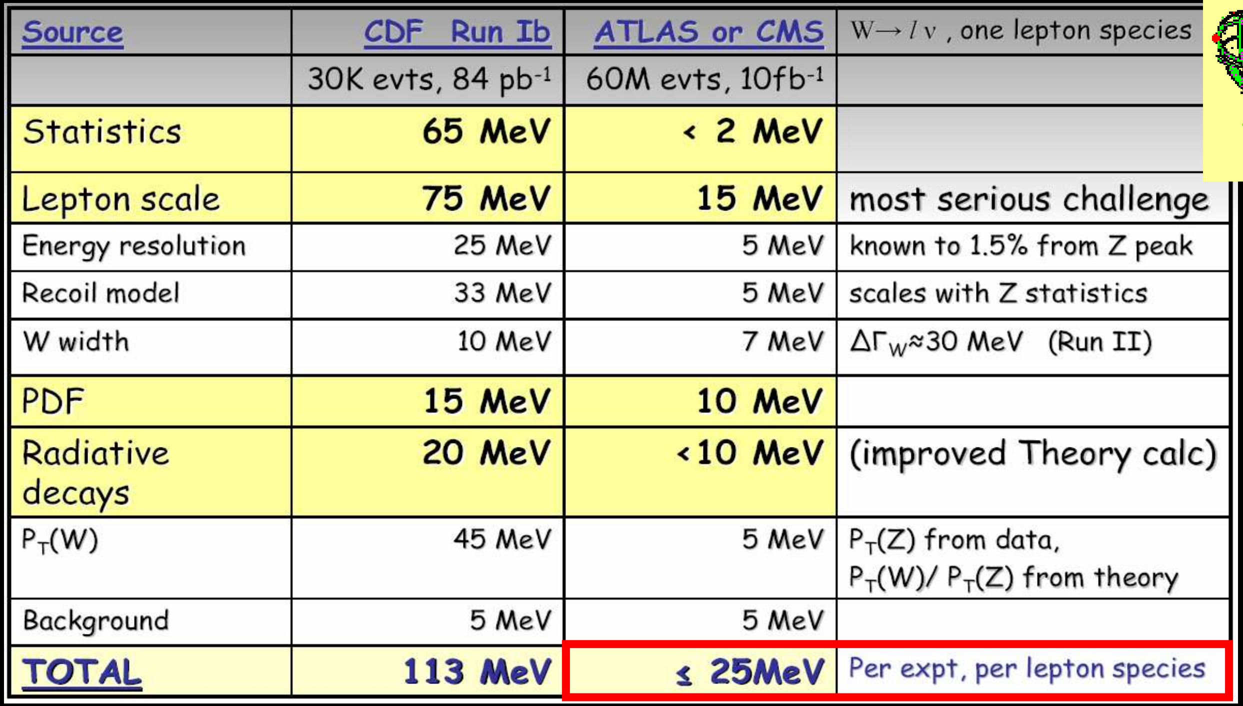
≈ 50 Z/s → ≈ 1.5 Z → ee /s

plus the same rates for muon decays!

- **W and Z events will provide an excellent tool for detector calibration**

W Mass at the LHC

ATLAS study:



Source	CDF Run Ib	ATLAS or CMS	$W \to l\nu$, one lepton species
	30K evts, 84 pb^{-1}	60M evts, 10fb^{-1}	
Statistics	65 MeV	< 2 MeV	
Lepton scale	75 MeV	15 MeV	most serious challenge
Energy resolution	25 MeV	5 MeV	known to 1.5% from Z peak
Recoil model	33 MeV	5 MeV	scales with Z statistics
W width	10 MeV	7 MeV	$\Delta\Gamma_W \approx 30$ MeV (Run II)
PDF	15 MeV	10 MeV	
Radiative decays	20 MeV	<10 MeV	(improved Theory calc)
$P_T(W)$	45 MeV	5 MeV	$P_T(Z)$ from data, $P_T(W)/P_T(Z)$ from theory
Background	5 MeV	5 MeV	
TOTAL	113 MeV	$\leq$ 25MeV	Per expt, per lepton species

- **Combine both channels & both experiments**

  $\Rightarrow$ $\Delta m_W \leq$ 15 MeV (LHC)

Compare to

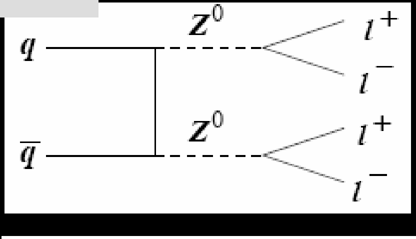
2007: $m_W = 80\,398 \pm 25$ MeV LEP & Tevatron Run I/II

2009: $m_W \approx 80 \; ... \; \pm 20$ MeV ($2.5 \cdot 10^{-4}$) expected after Tevatron Run II

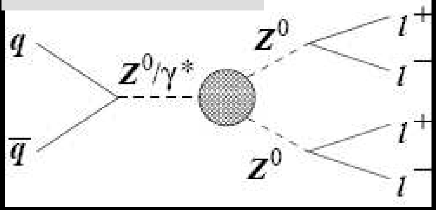
Di-Boson Production at the LHC

- **Very interesting: WW,ZZ final states not yet observed at the Tevatron**
  first WZ events observed early 2007
- **Test triple gauge boson couplings (TGC)**
  - **γWW and ZWW precisely fixed in SM**
  - **γZZ and ZZZ do not exist in SM!**

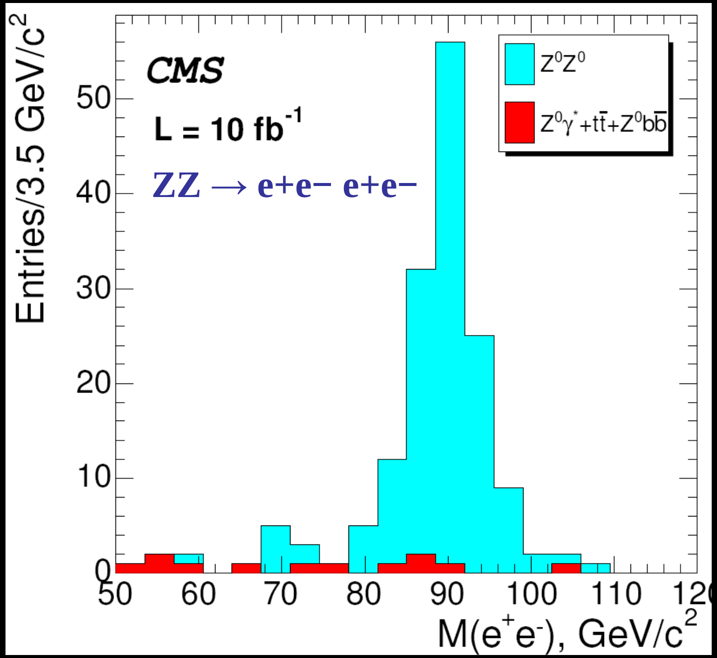
SM

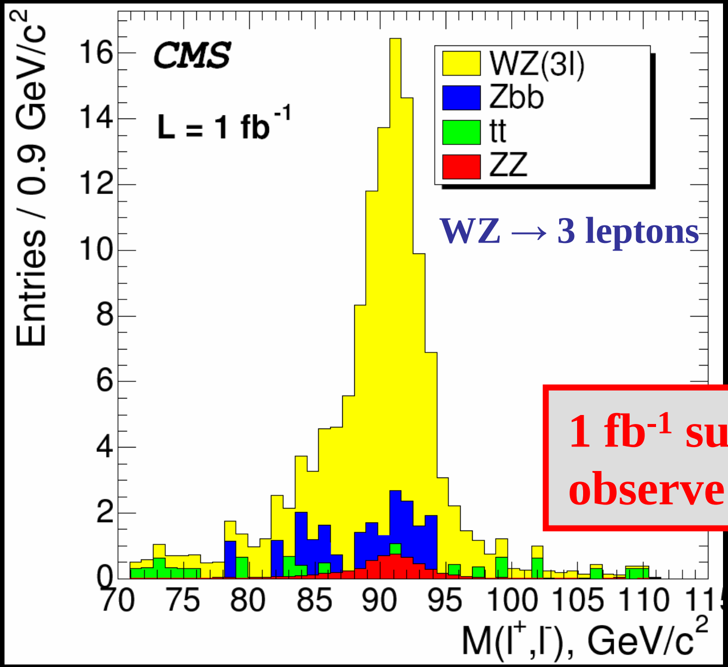


New physics



- **deviations from SM are amplified with E**
- **also Wγ and Zγ final states can be used**





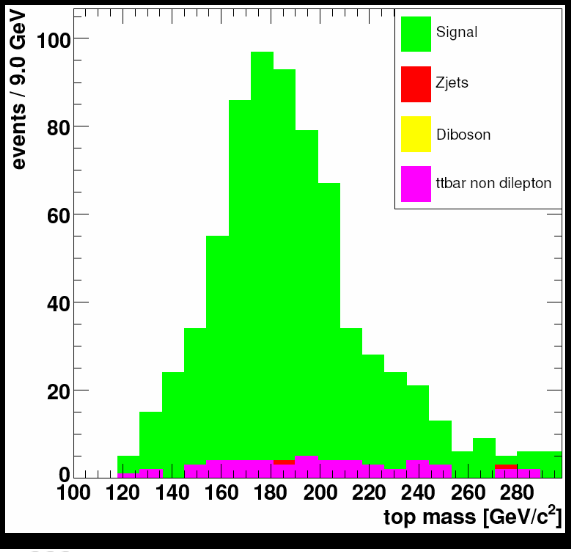
1 fb^{-1} sufficient to observe both processes

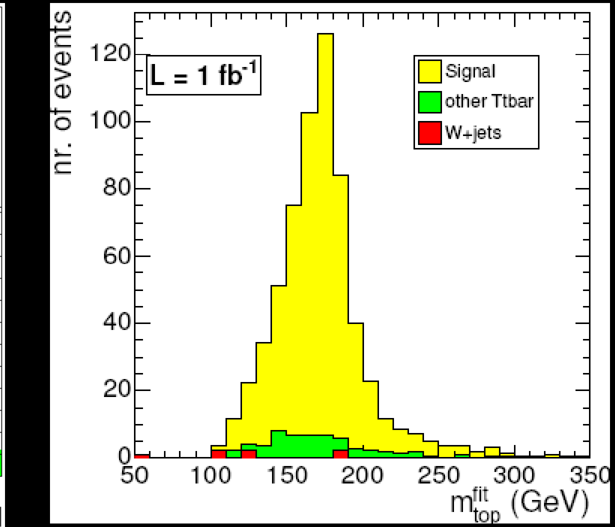
Top Mass at the LHC

Recent detailed studies by CMS:

di-leptonic

± 1.2 GeV



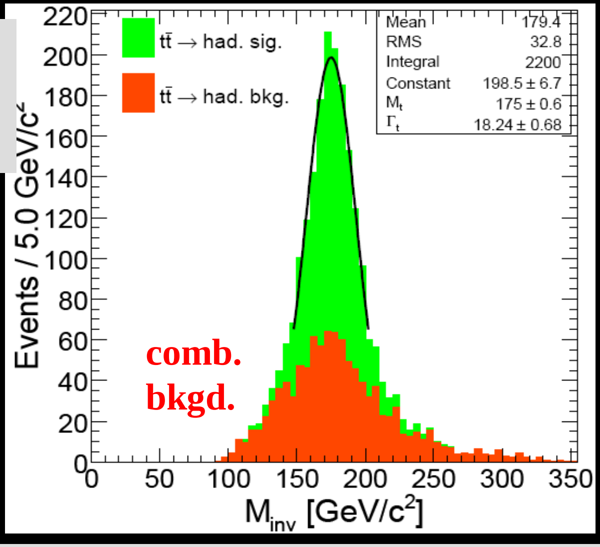


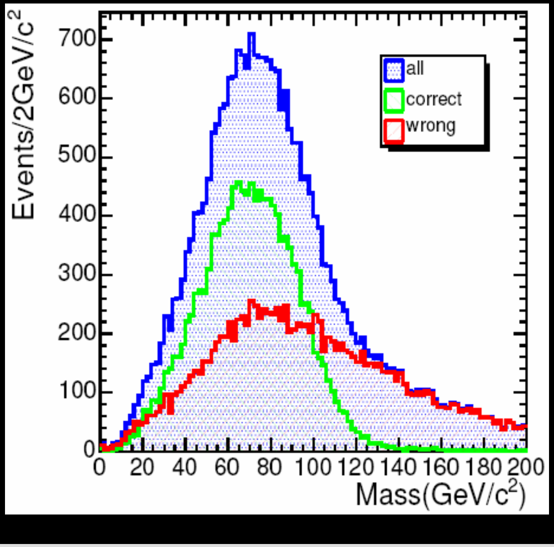
semi-leptonic

± 1.2 GeV

fully hadronic

± 2 GeV





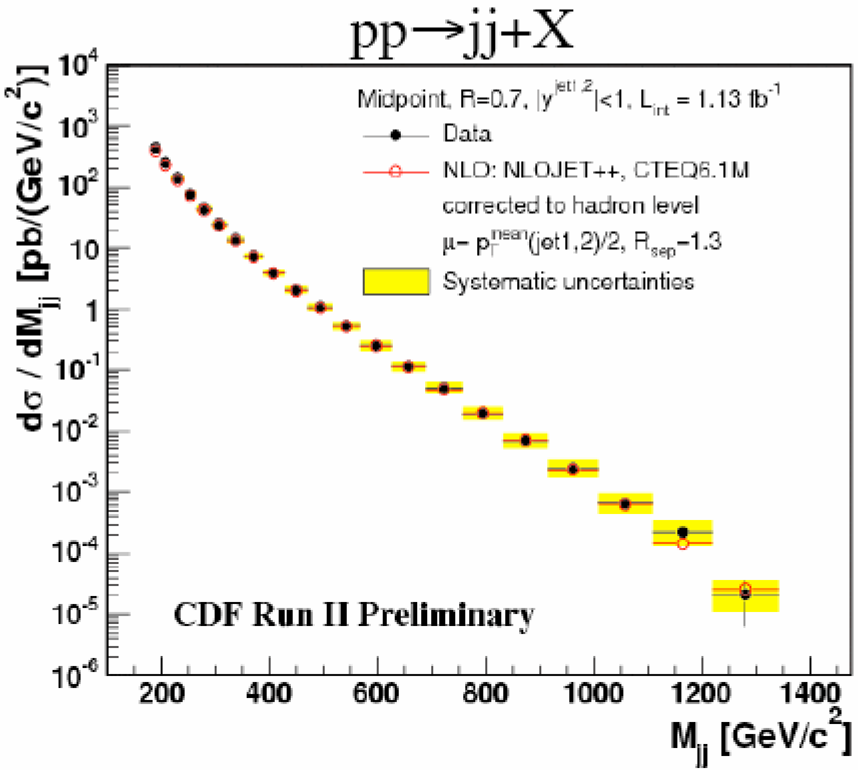
t→ J/Ψ + l + X

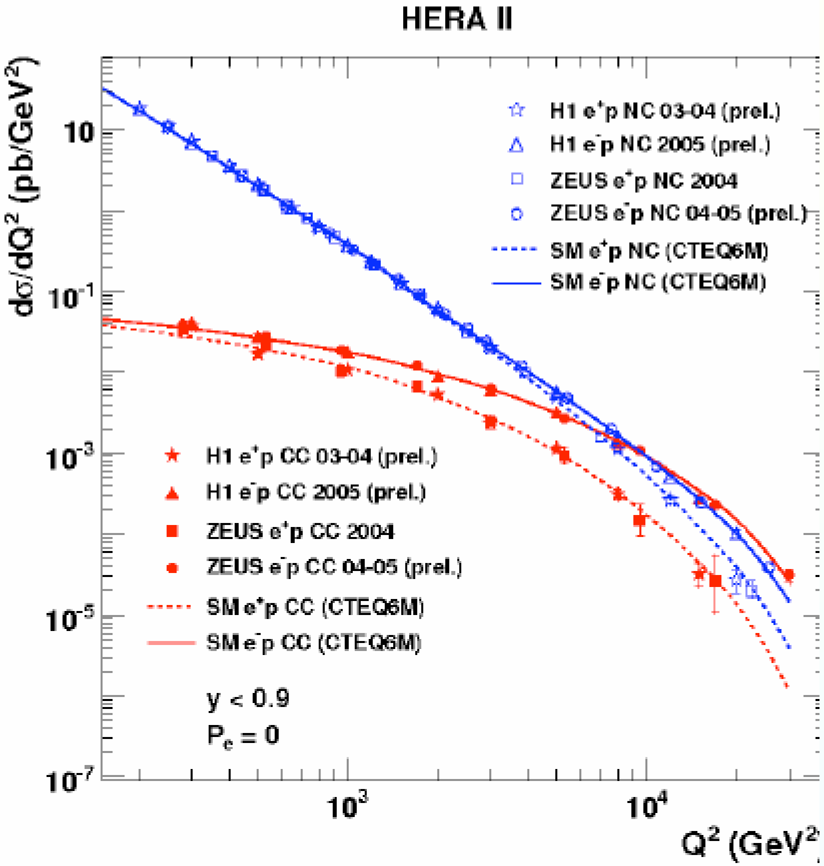
± 1.5 GeV

→ total top mass error ≤ 1 GeV possible with O(10 fb^{-1}) of well understood data

Testing the Standard Model

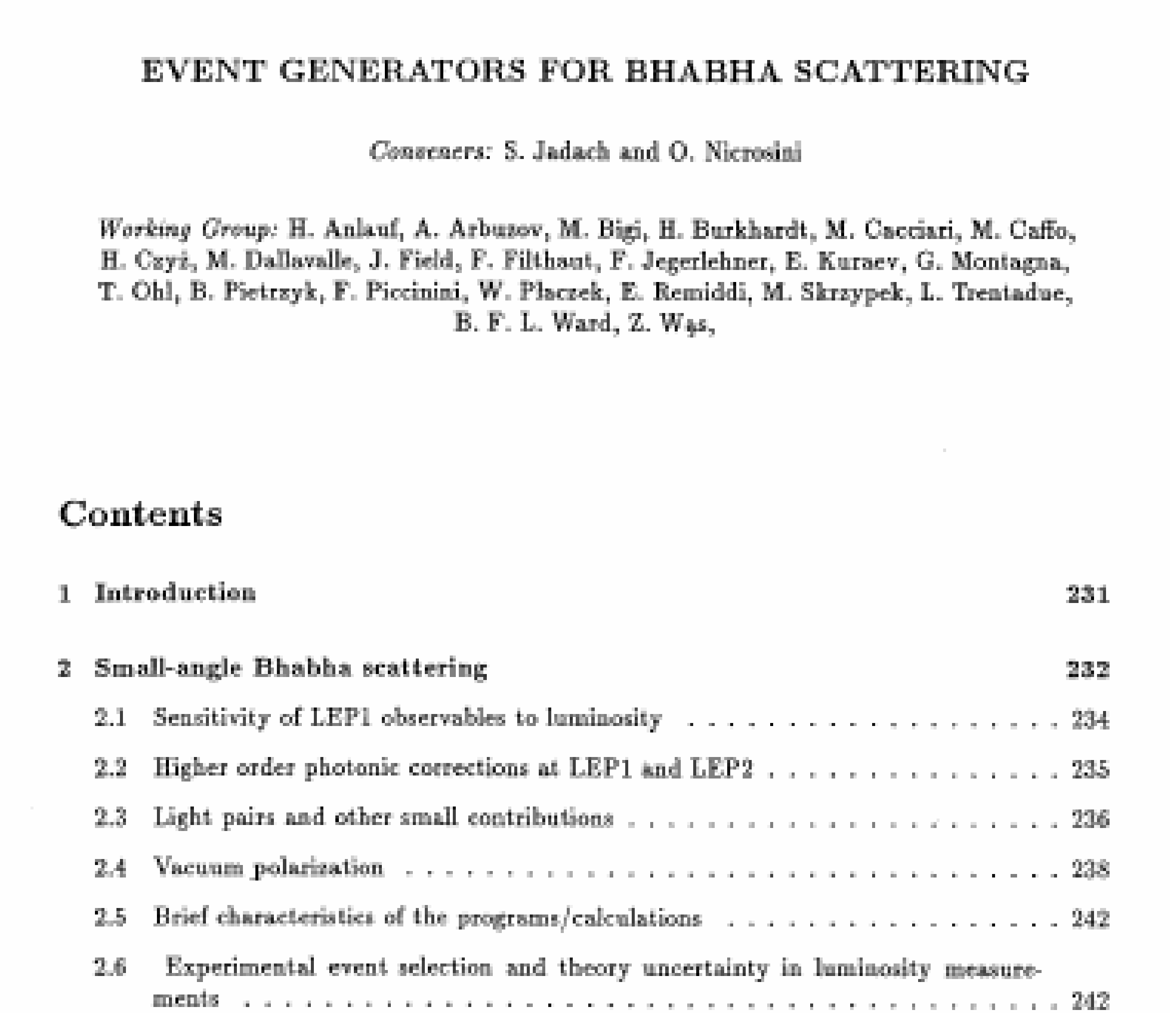
… and failing to find discrepancies





- Inclusive cross sections:
  - HERA: $d\sigma/dQ^2$ (CC and NC)
  - Tevatron: $d\sigma/dM(l^+l^-,jj,\gamma\gamma)$
- Excellent agreement with prediction over many orders

contributions since 1974 to the success of the Standard Model:



EVENT GENERATORS FOR BHABHA SCATTERING

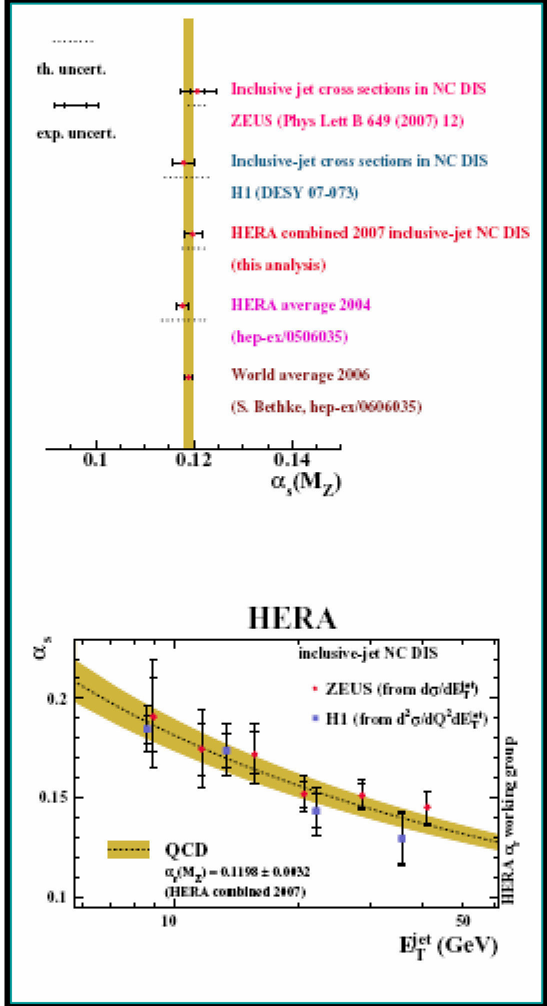
Conveners: S. Jadach and O. Nicrosini

Working Group: H. Anlauf, A. Arbuzov, M. Bigi, H. Burkhardt, M. Cacciari, M. Caffo, H. Czyż, M. Dallavalle, J. Field, F. Filthaut, F. Jegerlehner, E. Kuraev, G. Montagna, T. Ohl, B. Pietrzyk, F. Piccinini, W. Placzek, E. Remiddi, M. Skrzypek, L. Trentadue, B. F. L. Ward, Z. Wąs,

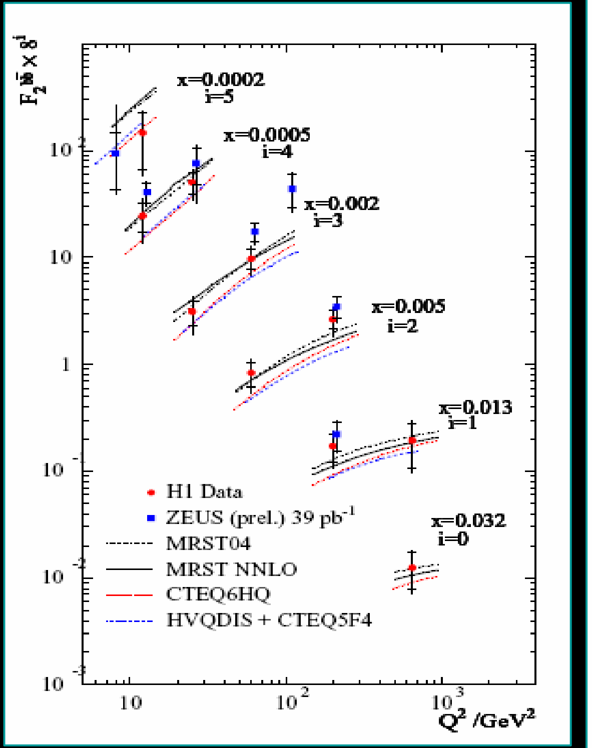
Contents

Precision QCD Measurements

New from HERA

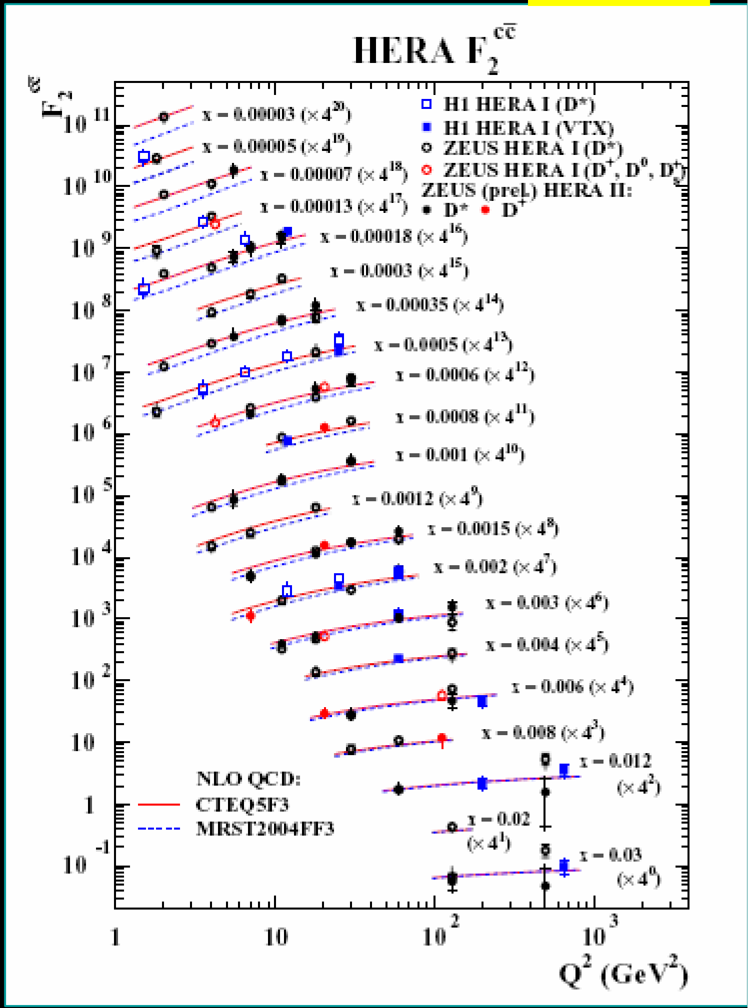


α_s

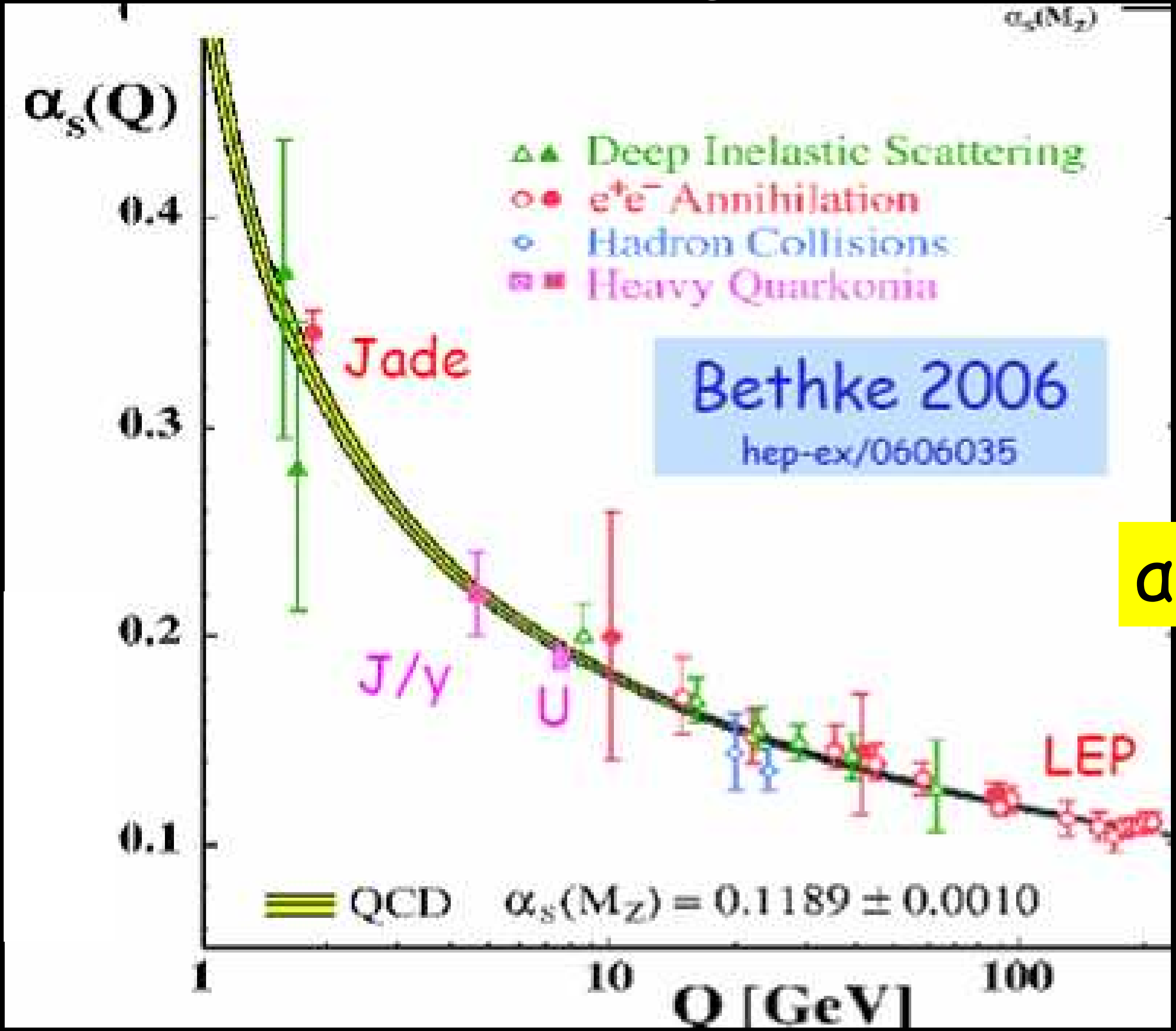


F_2^{bb}

F_2^{cc}



QCD



α_s

0.1189
± 0.0010

O Behnke

QCD

Measurement of α_s at LHC limited by

- PDF (3%)
- Renormalisation & factorisation scale (7%)
- Parametrisaton (A,B)

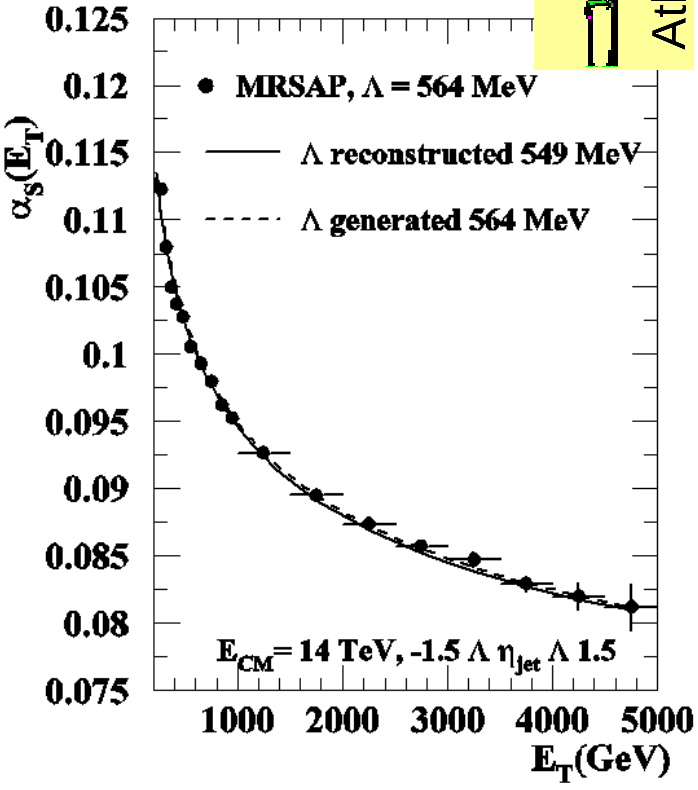
$$\frac{d\sigma}{dE_T} \sim \alpha_S^2(\mu_R)A(E_T) + \alpha_S^3(\mu_R)B(E_T)$$

- 10% accuracy $\alpha_s(m_Z)$ from incl. jets
- Improvement from 3-jet to 2-jet rate?

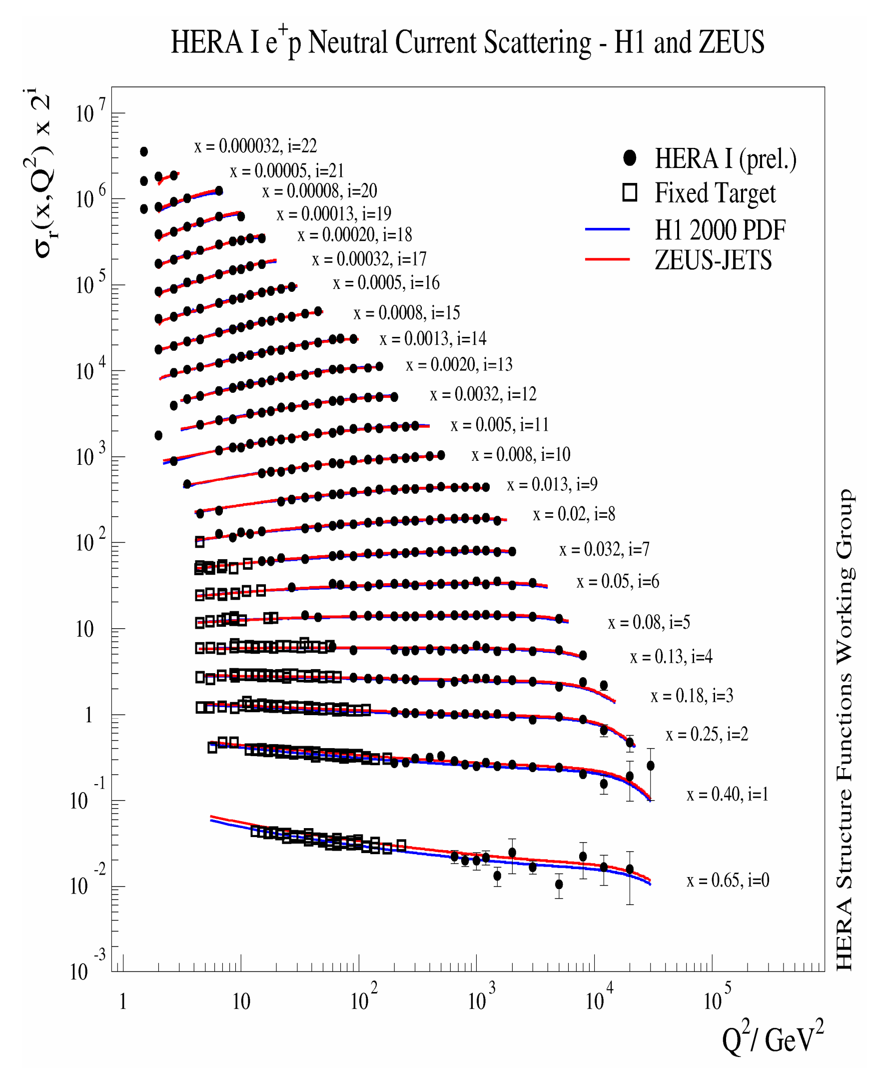
Verification of running of α_s and test of QCD at the smallest distance scale

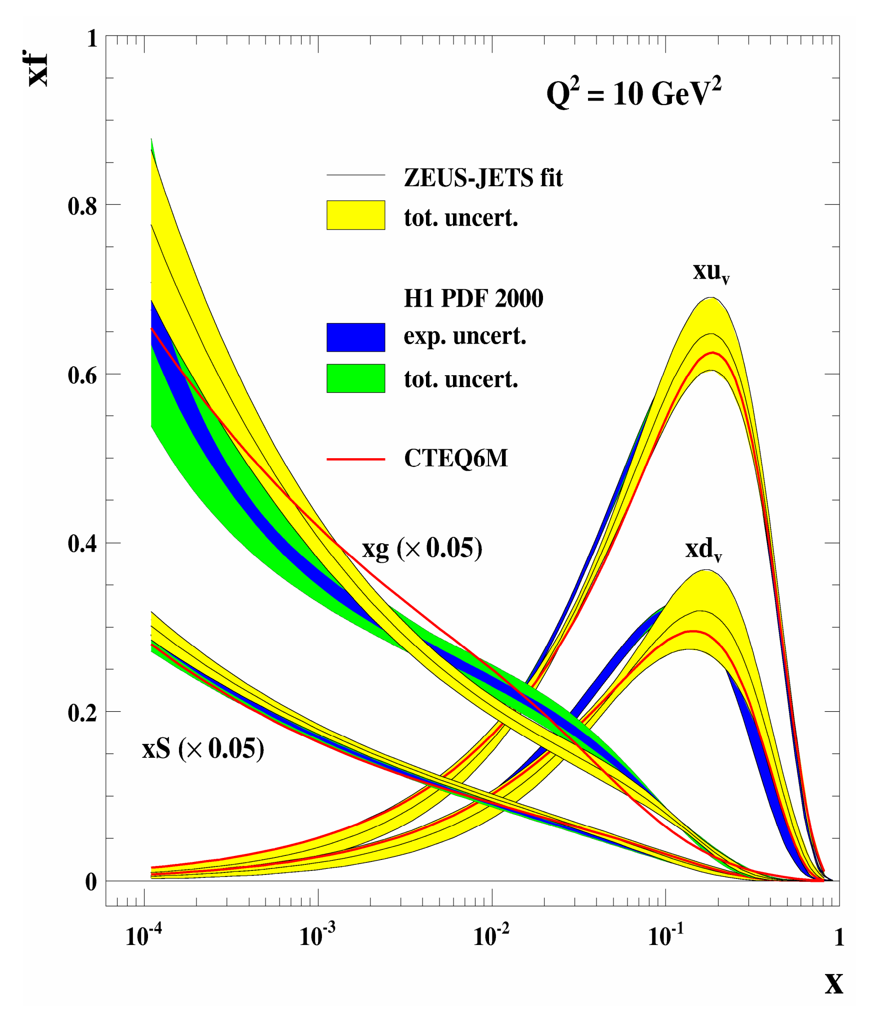
- $\alpha_s = 0.118$ at m_Z
- $\alpha_s \approx 0.082$ at 4 TeV (QCD expectation)

Atlas



Proton Structure Measurements

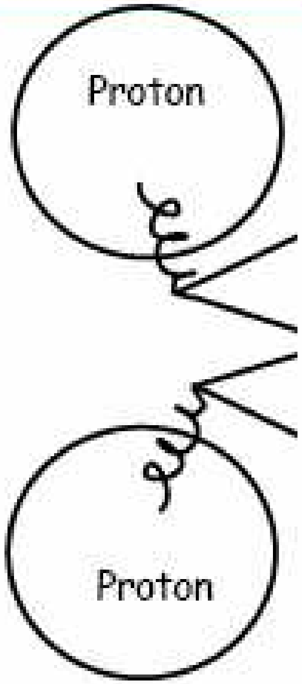




Talk by Claire Gwenlan

HERA proton PDF --> LHC W production

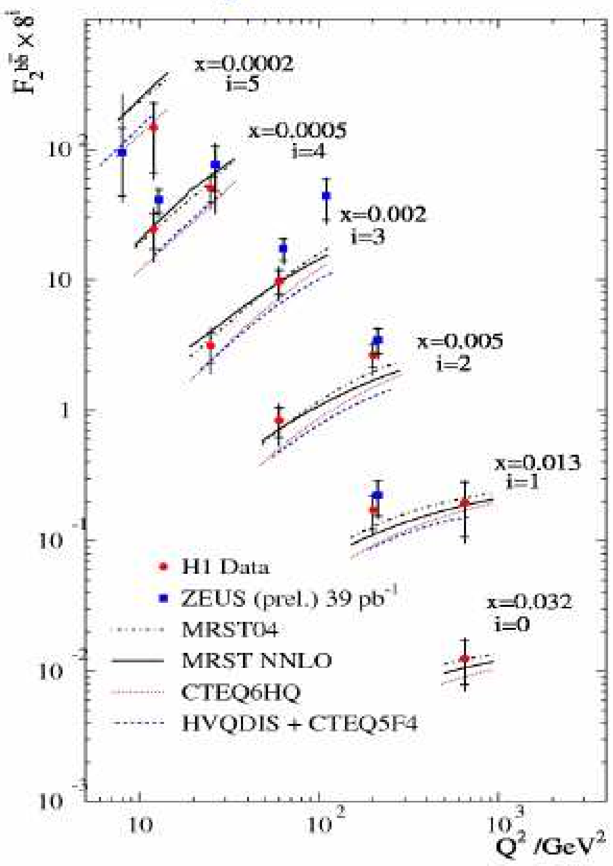
Prediction using ZEUS-S-PDF

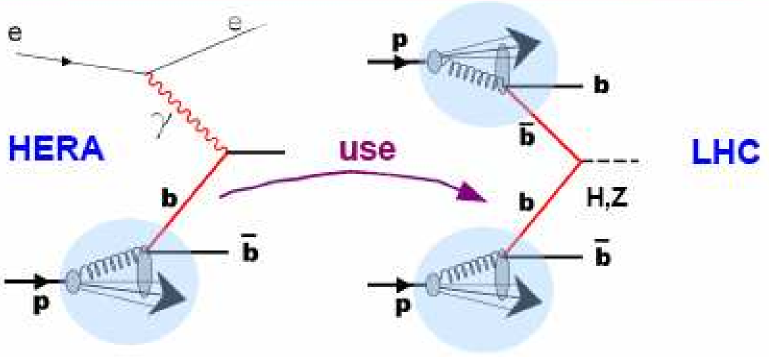


'Lumi' process

HERA beauty density ... goes to LHC

Beauty contribution to F2



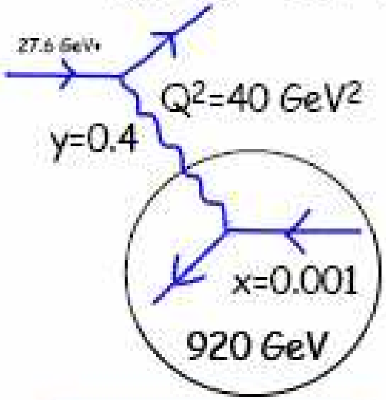


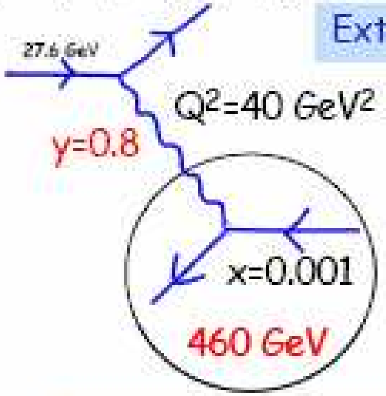
- ➔ 'Beautyful' new HERA II data
- ➔ Astounding spread of model predictions!

Gluon density via F_L at HERA

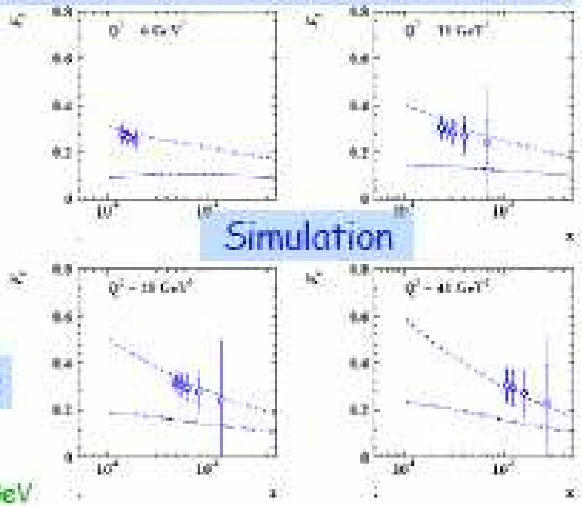
$$F_L = \frac{\alpha_S}{4\pi} x^2 \int_x^1 \frac{dz}{z^3}\left[\frac{16}{3}F_2 + 8\sum e_q^2 (1 - x/z) zg\right]$$

$\sigma_r(x,Q^2) = F_2(x,Q^2) - y^2/y_+ F_L(x,Q^2) \rightarrow$



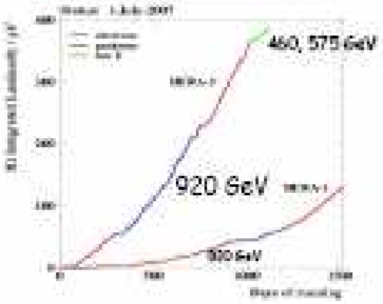


Extract F_L from $\sigma_r(x,Q^2)$ at different y

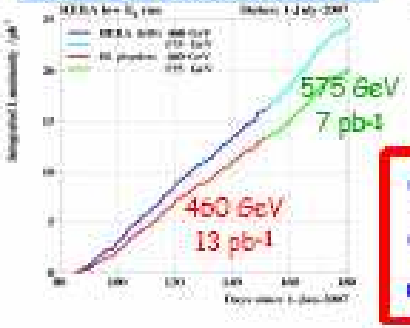


Simulation

HERA: All runs



Last 3 HERA months

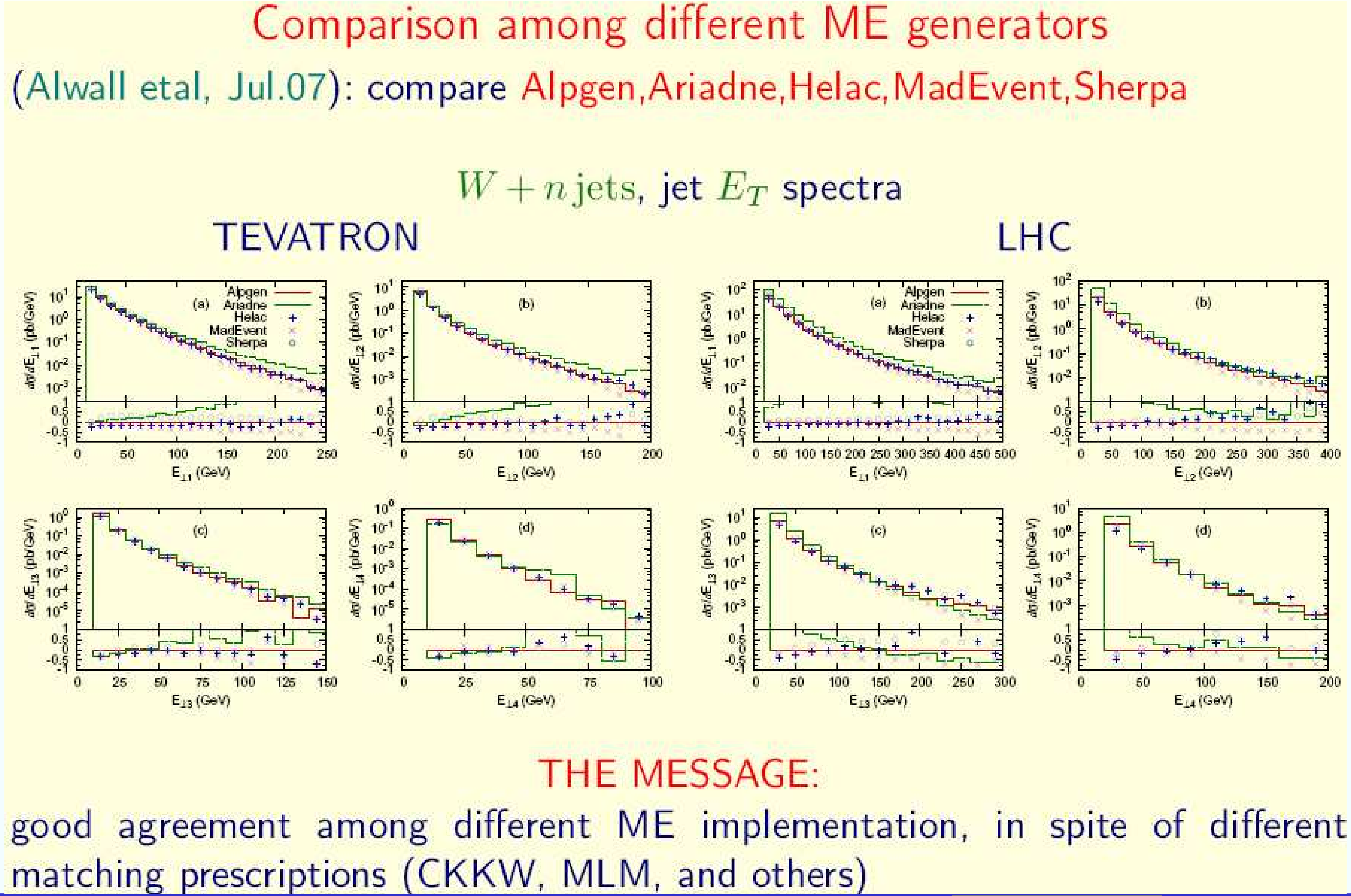


→ Nice low E_p data on tape ☺

→ Final F_L should separate extreme gluon densities

QCD Monte Carlo Calculations

- **Increasingly sophisticated algorithms**
- **Several different approaches**
  - **Many cross-checks**



Comparison among different ME generators

(Alwall etal, Jul.07): compare Alpgen,Ariadne,Helac,MadEvent,Sherpa

$W + n\,$jets, jet E_T spectra

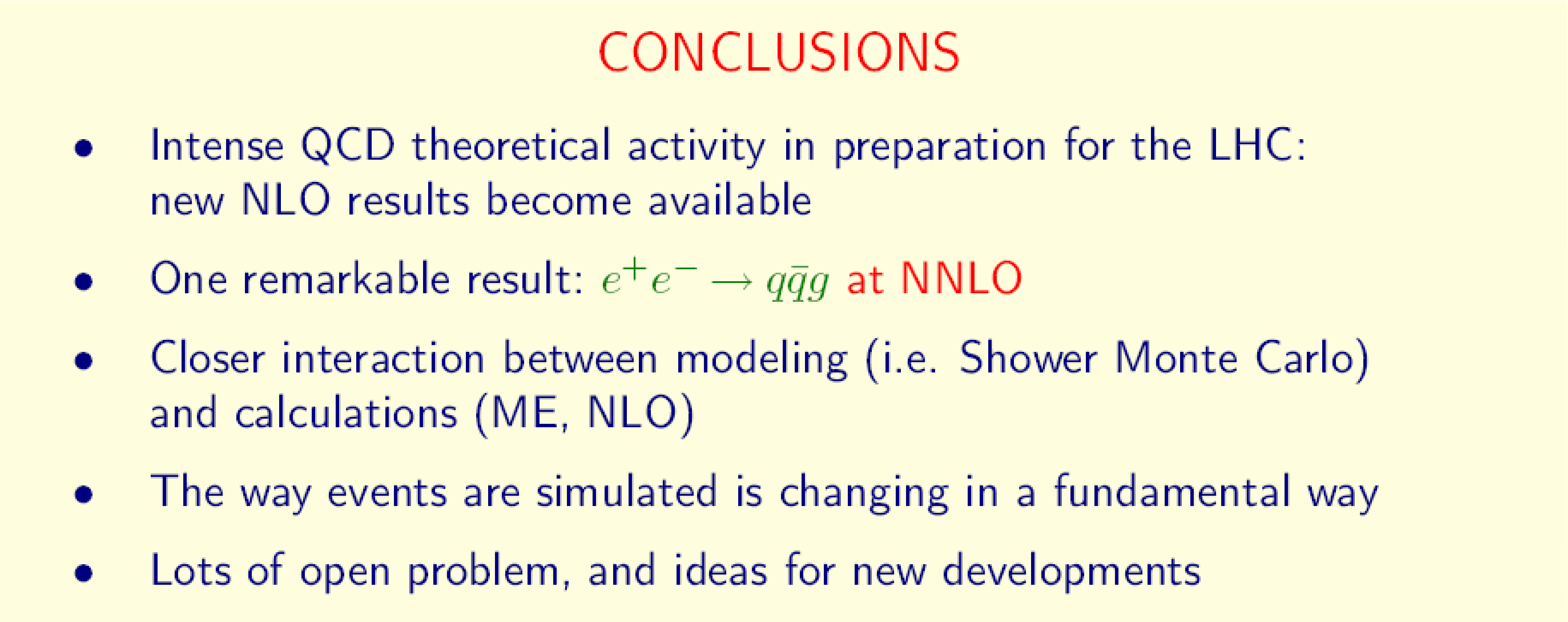
TEVATRON

LHC

THE MESSAGE:

good agreement among different ME implementation, in spite of different matching prescriptions (CKKW, MLM, and others)

QCD (Monte Carlo) Calculations

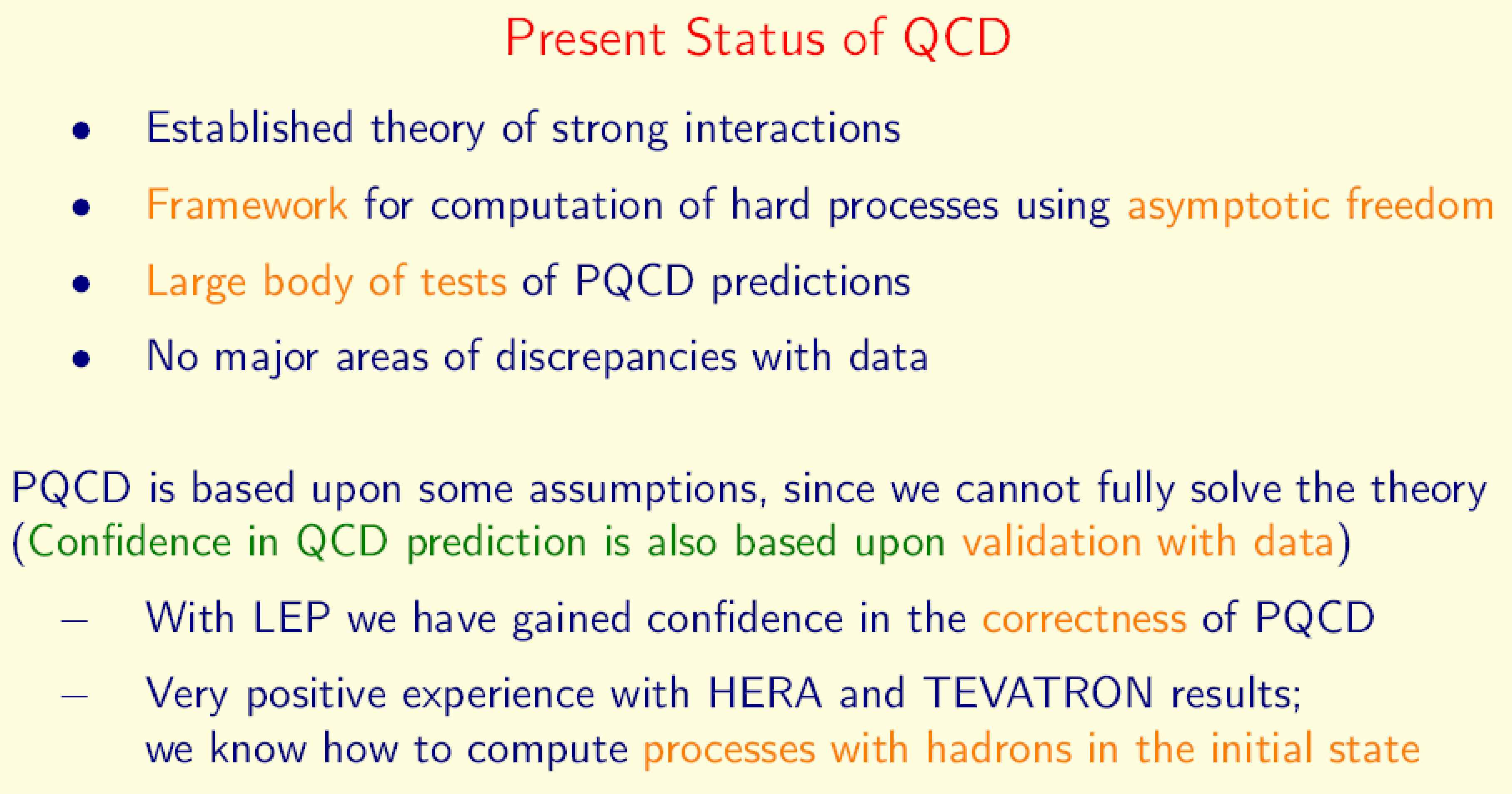


CONCLUSIONS

- Intense QCD theoretical activity in preparation for the LHC: new NLO results become available
- One remarkable result: $e^+e^- \rightarrow q\bar{q}g$ at NNLO
- Closer interaction between modeling (i.e. Shower Monte Carlo) and calculations (ME, NLO)
- The way events are simulated is changing in a fundamental way
- Lots of open problem, and ideas for new developments

Nason

QCD



Present Status of QCD

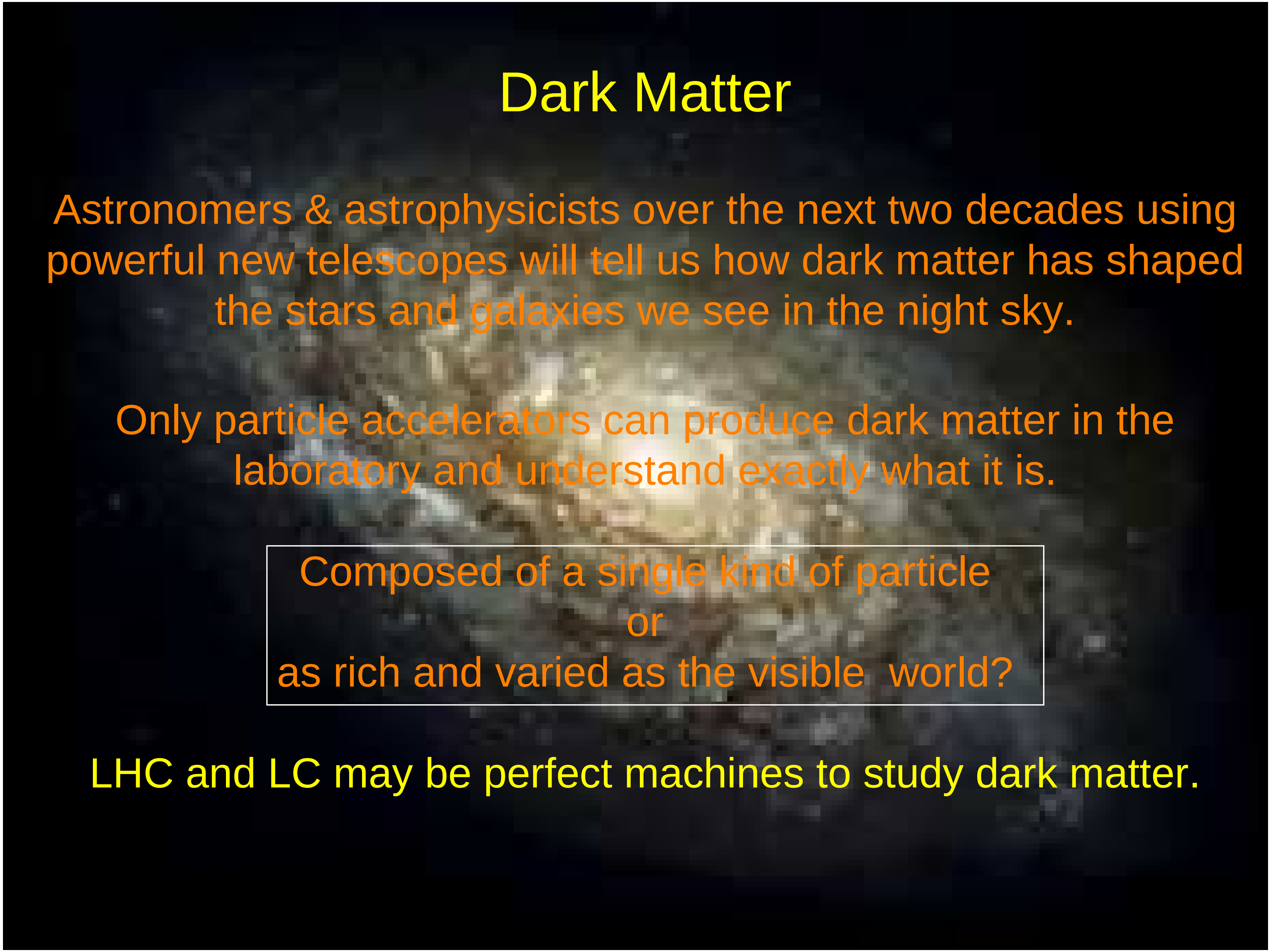
- Established theory of strong interactions
- Framework for computation of hard processes using asymptotic freedom
- Large body of tests of PQCD predictions
- No major areas of discrepancies with data

PQCD is based upon some assumptions, since we cannot fully solve the theory (Confidence in QCD prediction is also based upon validation with data)

- With LEP we have gained confidence in the correctness of PQCD
- Very positive experience with HERA and TEVATRON results;
  we know how to compute processes with hadrons in the initial state

Nason

Entering the Dark World



Dark Matter

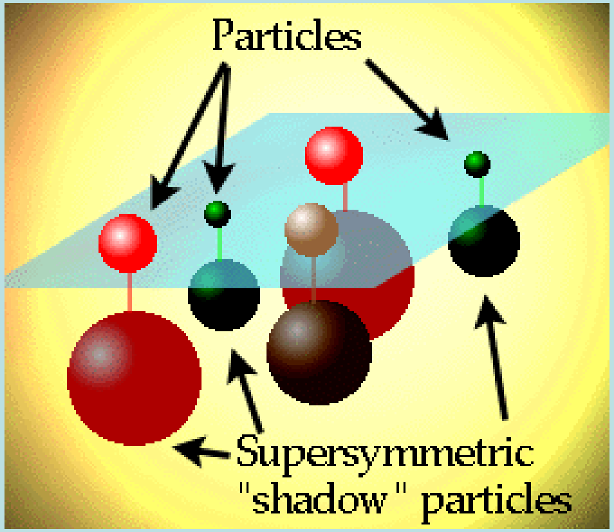
Astronomers & astrophysicists over the next two decades using powerful new telescopes will tell us how dark matter has shaped the stars and galaxies we see in the night sky.

Only particle accelerators can produce dark matter in the laboratory and understand exactly what it is.

Composed of a single kind of particle
or
as rich and varied as the visible world?

LHC and LC may be perfect machines to study dark matter.

Supersymmetry



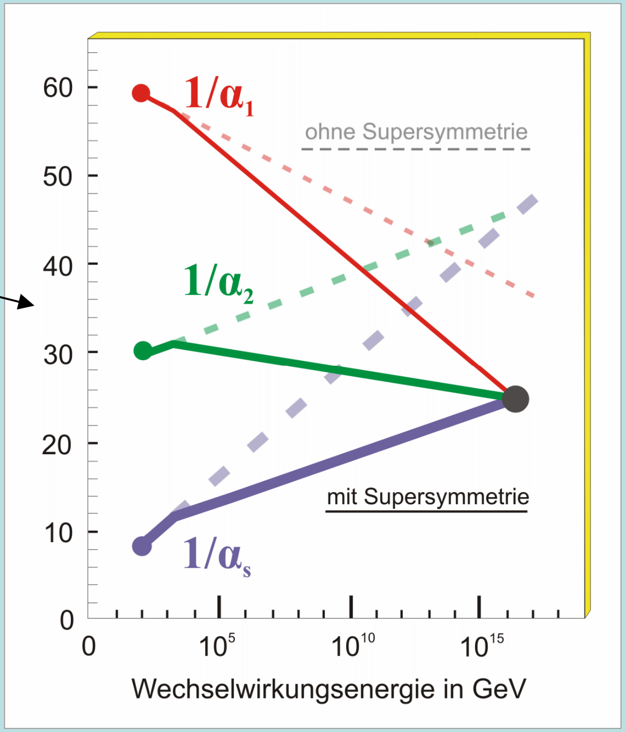
- unifies matter with forces

  for each particle a supersymmetric partner (*sparticle*) of opposite statistics is introduced

- allows to unify strong and electroweak forces

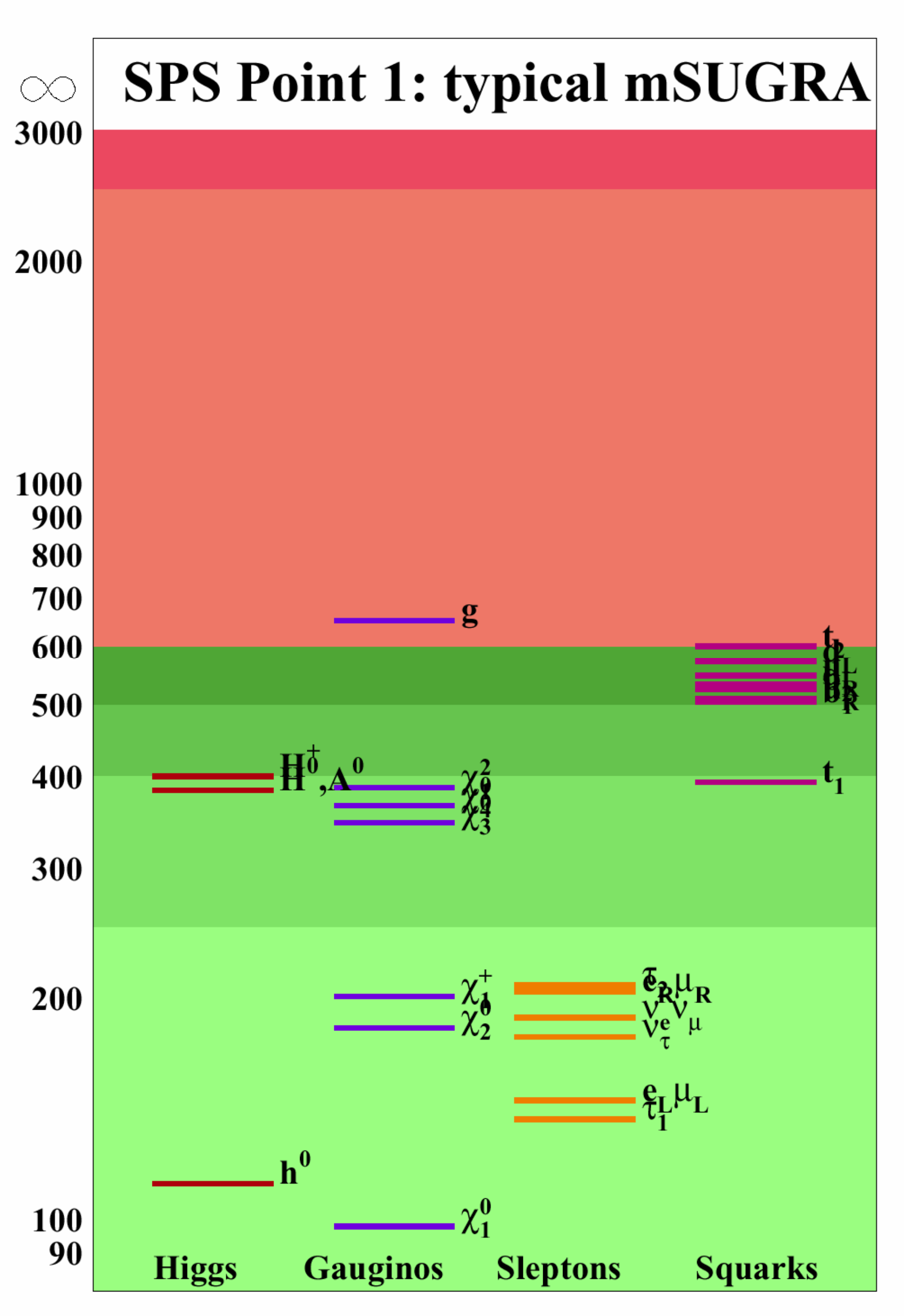
  $\sin^2\theta_W{}^{SUSY} = 0.2335(17)$

  $\sin^2\theta_W{}^{exp} = 0.2315(2)$



- provides link to string theories
- provides Dark Matter candidate

Supersymmetry

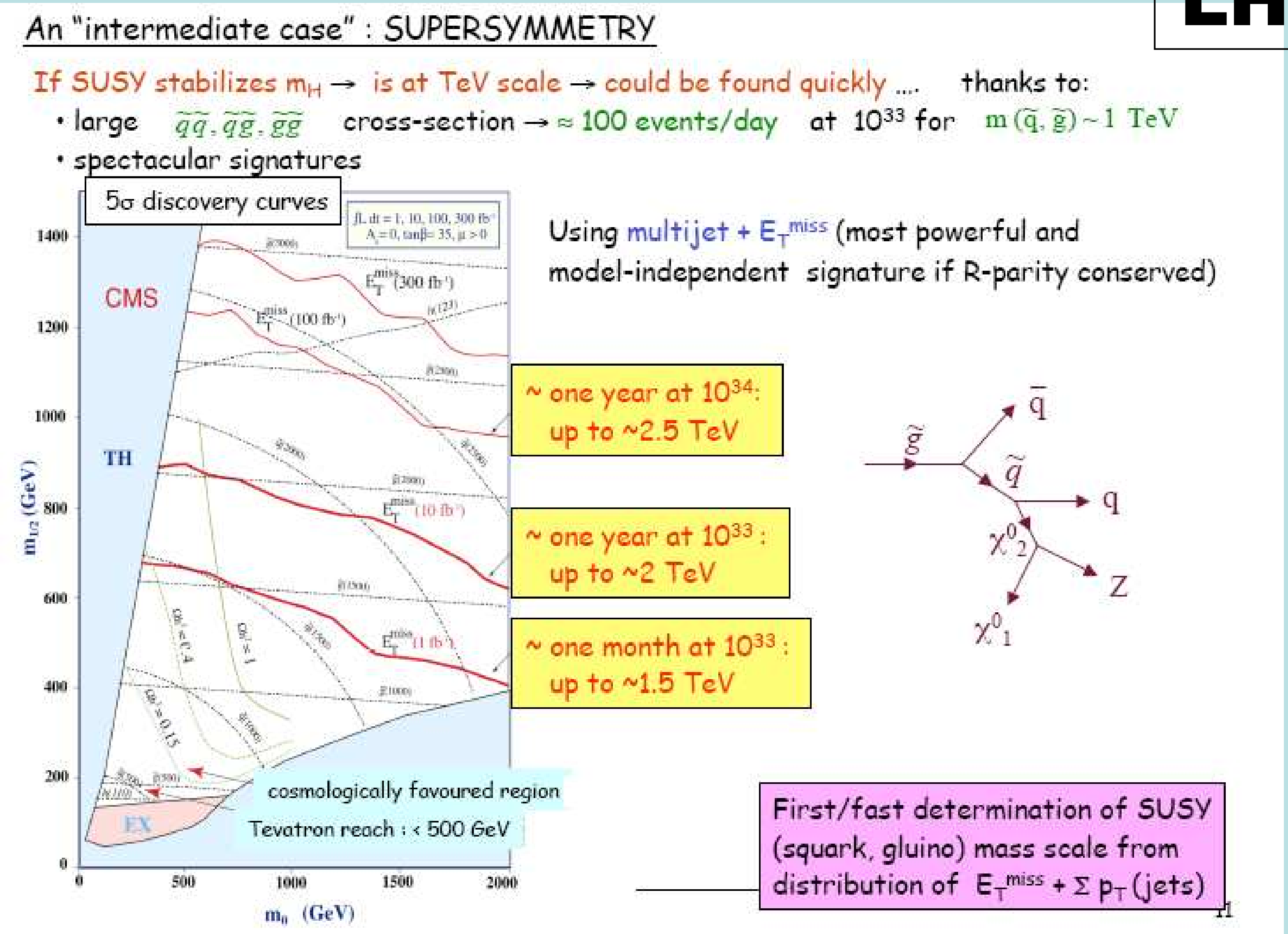


Mass spectra depend on choice of models and parameters...

well measureable at LHC

precise spectroscopy at ILC / CLIC

LHC



An "intermediate case" : SUPERSYMMETRY

If SUSY stabilizes m_H → is at TeV scale → could be found quickly .... thanks to:

- large $\tilde{q}\tilde{q}, \tilde{q}\tilde{g}, \tilde{g}\tilde{g}$ cross-section → ≈ 100 events/day at 10^{33} for $m(\tilde{q}, \tilde{g}) \sim 1$ TeV
- spectacular signatures

5σ discovery curves

cosmologically favoured region

Tevatron reach : < 500 GeV

~ one year at 10^{34}: up to ~2.5 TeV

~ one year at 10^{33} : up to ~2 TeV

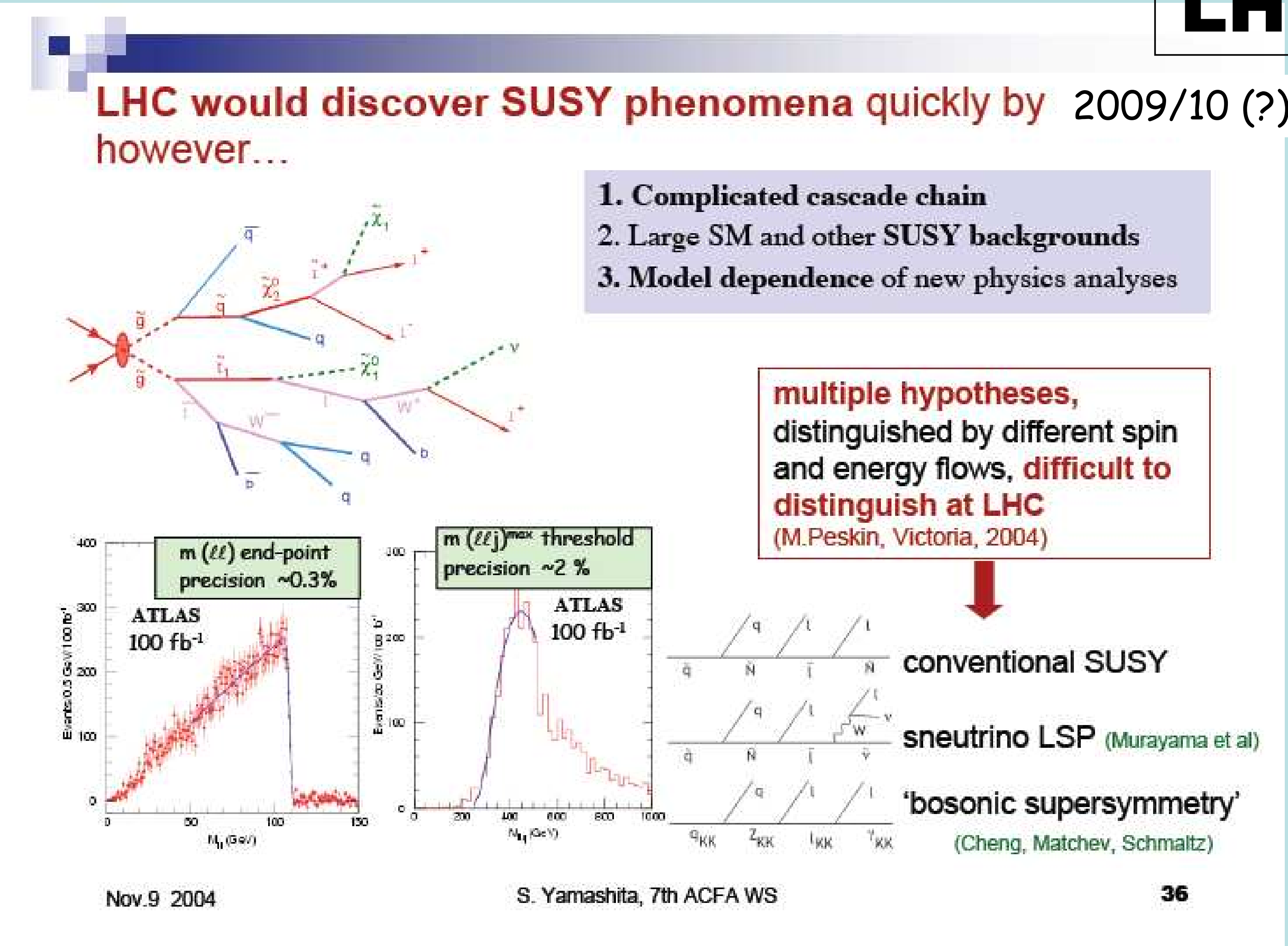
~ one month at 10^{33} : up to ~1.5 TeV

Using multijet + E_T^{miss} (most powerful and model-independent signature if R-parity conserved)

First/fast determination of SUSY (squark, gluino) mass scale from distribution of $E_T^{miss} + \Sigma\, p_T$(jets)

from F. Gianotti (LP05)

LHC



LHC would discover SUSY phenomena quickly by 2009/10 (?) however…

1. Complicated cascade chain

2. Large SM and other **SUSY backgrounds**

3. Model dependence of new physics analyses

multiple hypotheses, distinguished by different spin and energy flows, **difficult to distinguish at LHC**
(M.Peskin, Victoria, 2004)

m (ℓℓ) end-point
precision ~0.3%

ATLAS
100 fb-1

m (ℓℓj)max threshold
precision ~2 %

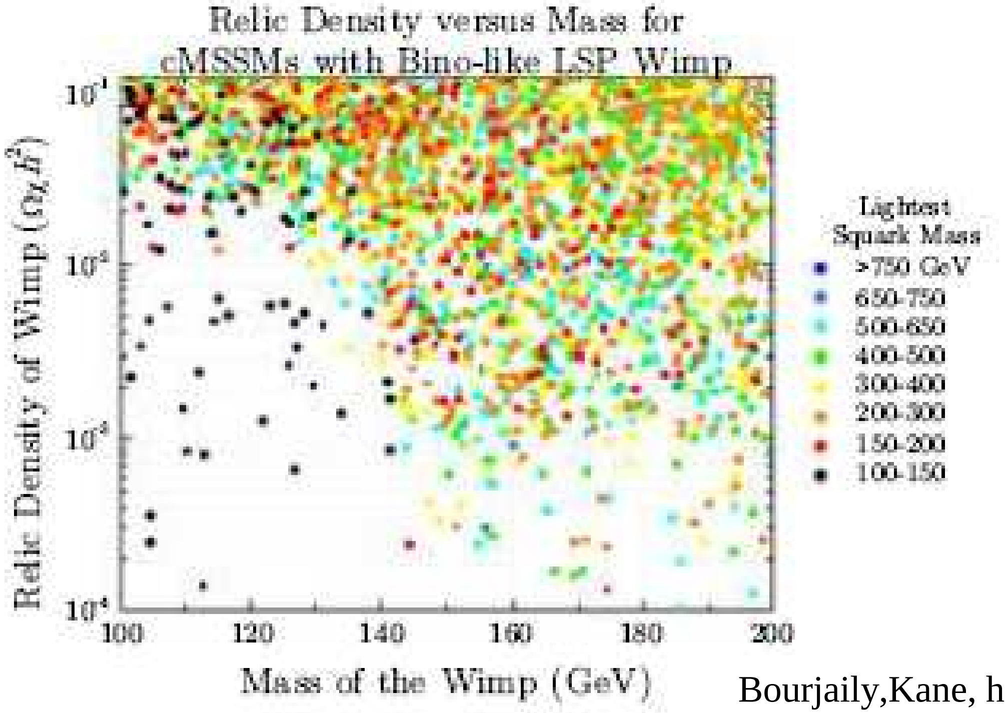
ATLAS
100 fb-1

conventional SUSY

sneutrino LSP (Murayama et al)

'bosonic supersymmetry'
(Cheng, Matchev, Schmaltz)

LSP responsible for relic density Ω_{CDM} ?



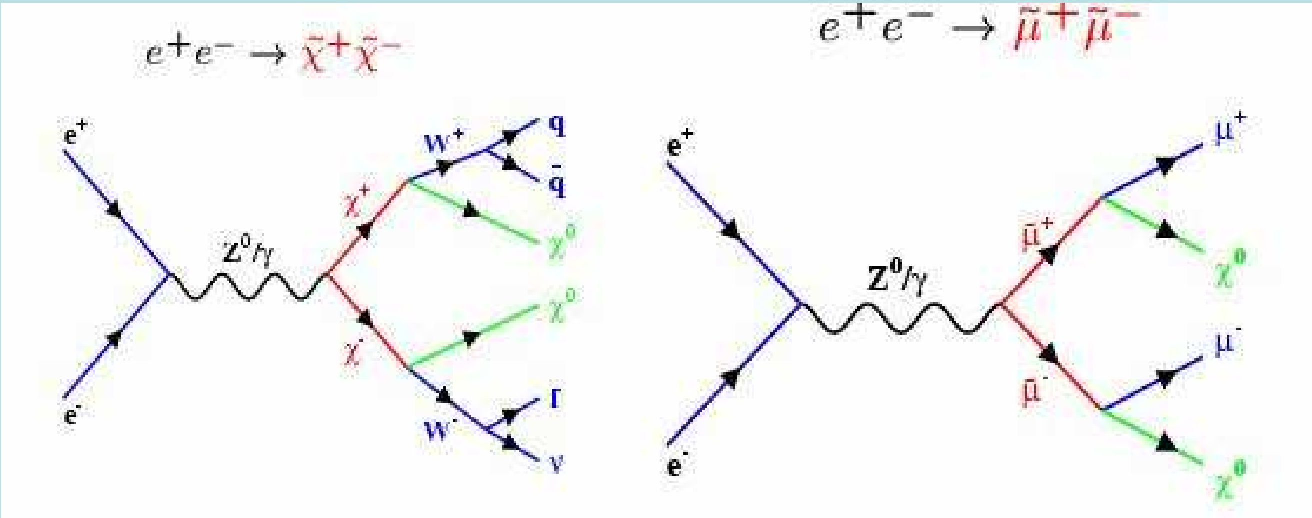
Bourjaily,Kane, hep-ph/0501262

→ need to measure many parameters, in particular coupling to matter

Supersymmetry

Production and decay of
supersymmetric particles
at e^+e^- colliders

ILC



charginos

s-muons

Lightest supersymmetric particle stable in most models

➡ candidate for dark matter

Experimental signature: missing energy

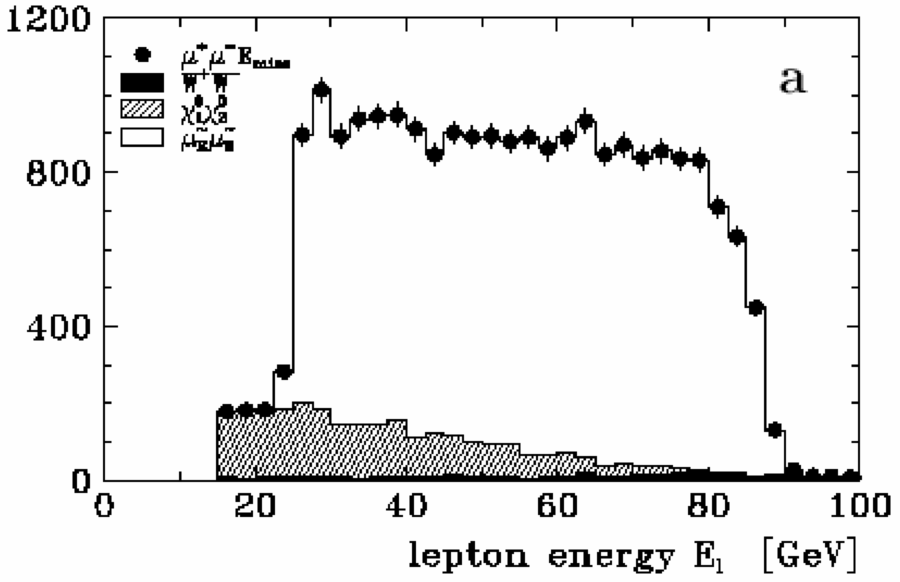
Measurement of sparticle properties masses, couplings, quantum numbers,…

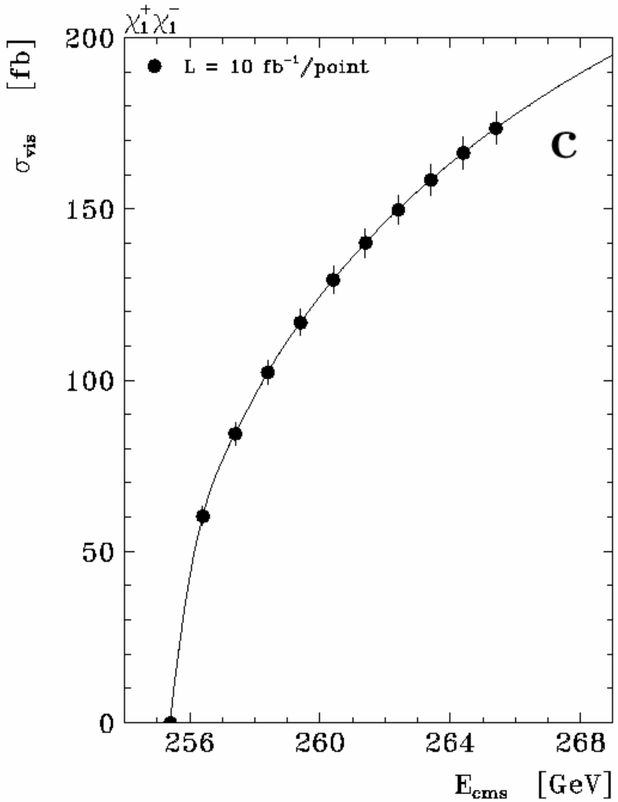
ILC

ex: Sleptons

lepton energy spectrum in continuum

ex: Charginos threshold scan



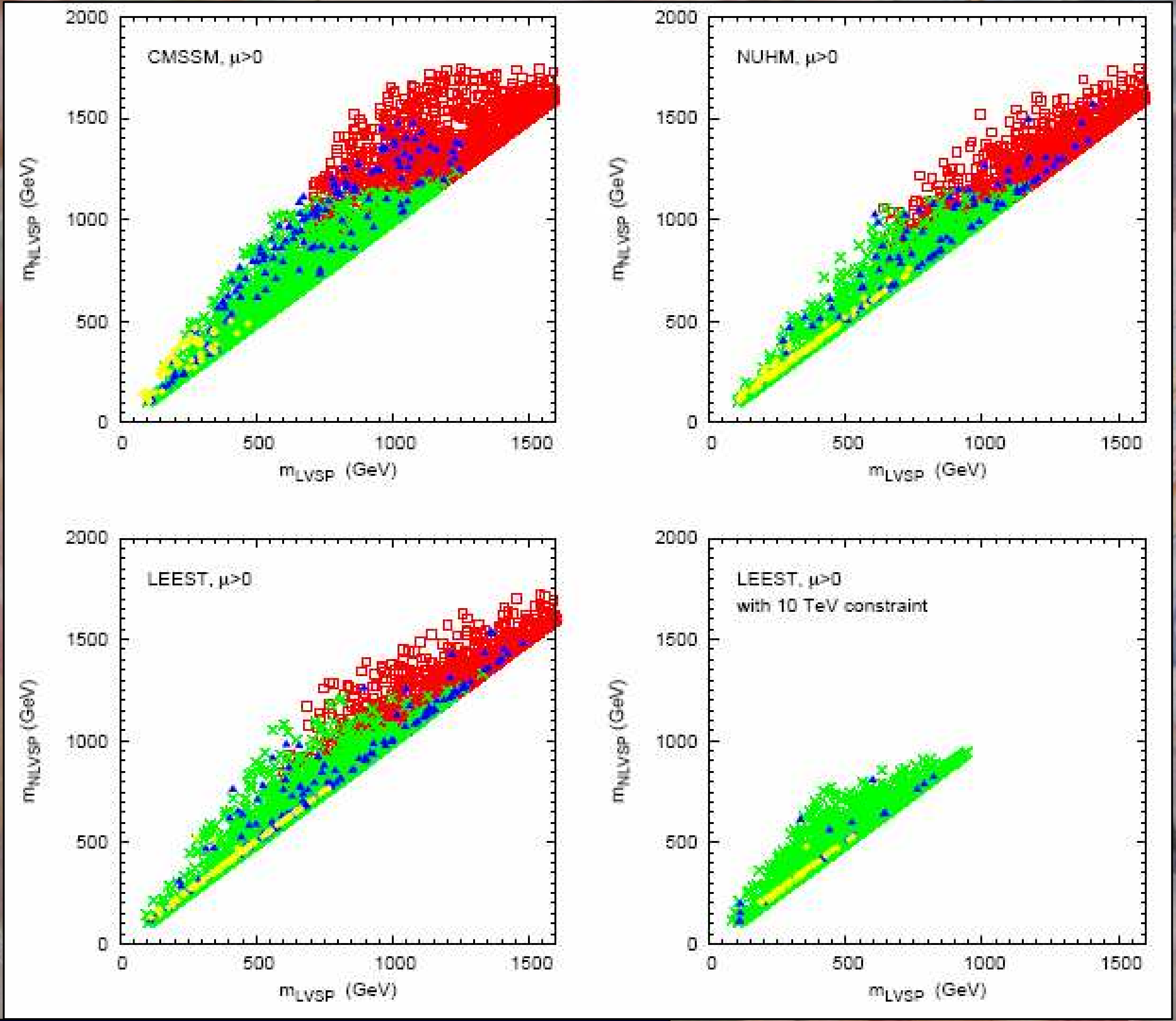


achievable accuracy:

$\delta m/m \sim 10^{-3}$

BUT

Sparticles may not be very light



← Second lightest visible sparticle

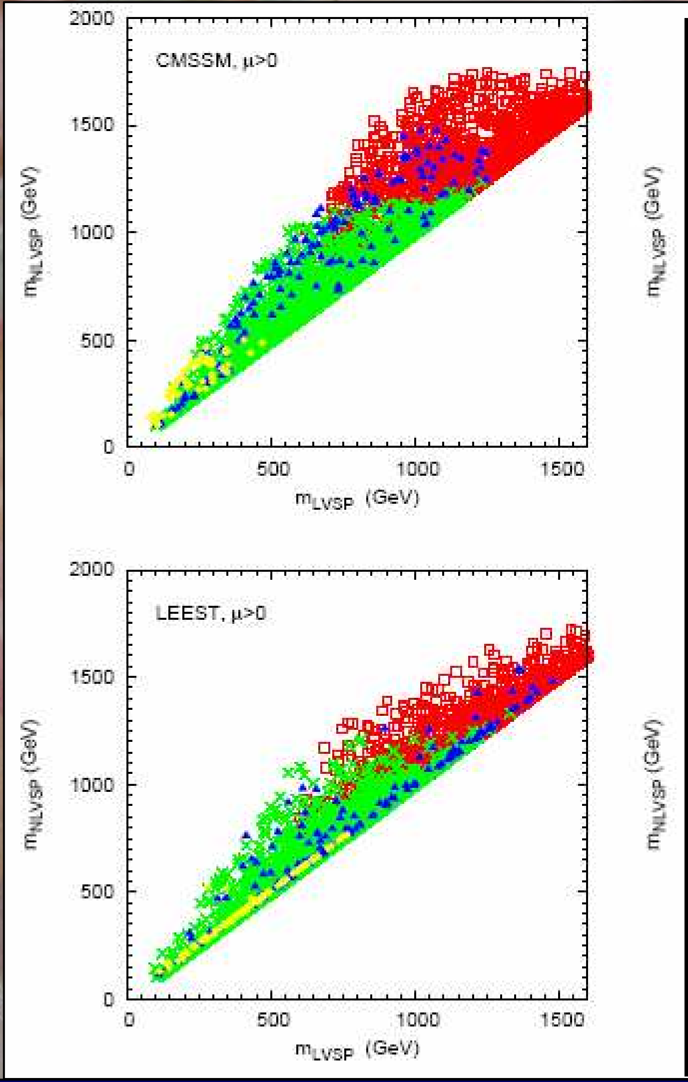
Lightest visible sparticle →

JE + Olive + Santoso + Spanos

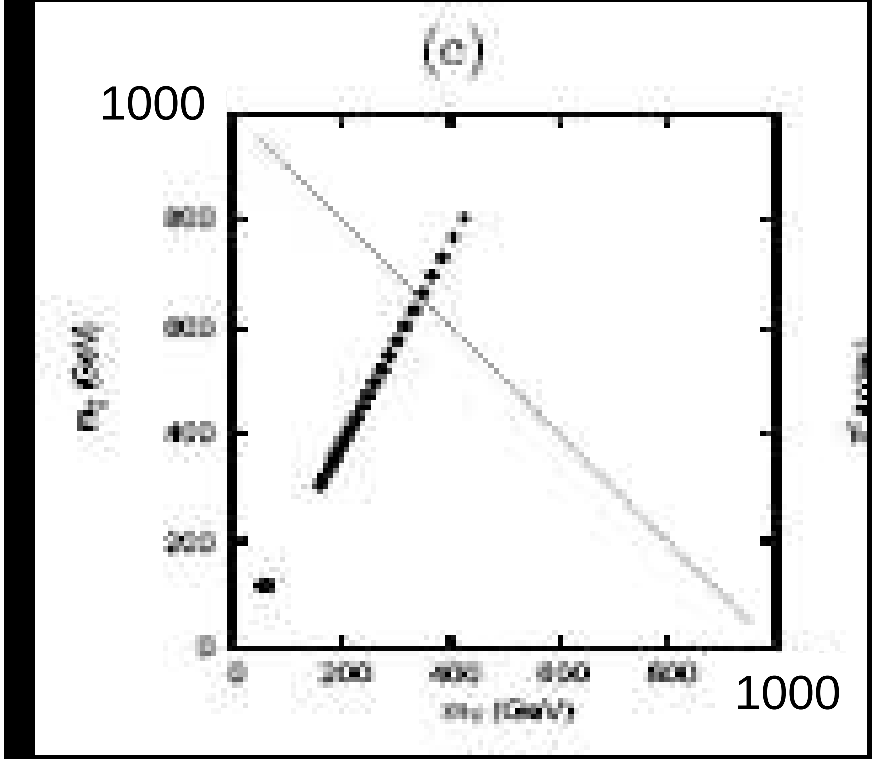
BUT

LSP light in most cases

← Second lightest visible sparticle



Lightest visible sparticle →



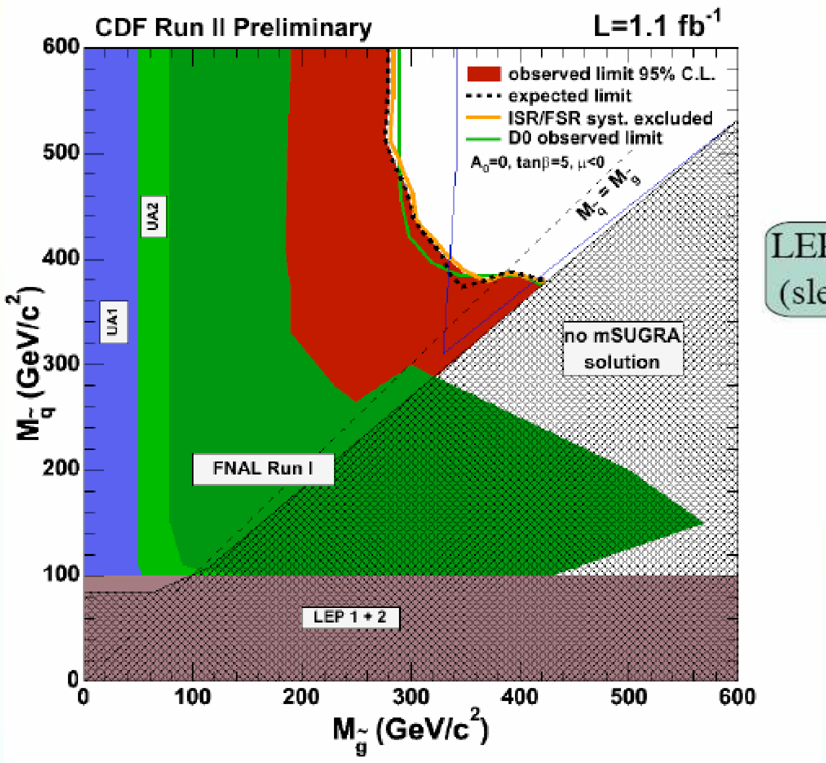
Lightest visible sparticle →

Lightest invisible sparticle →

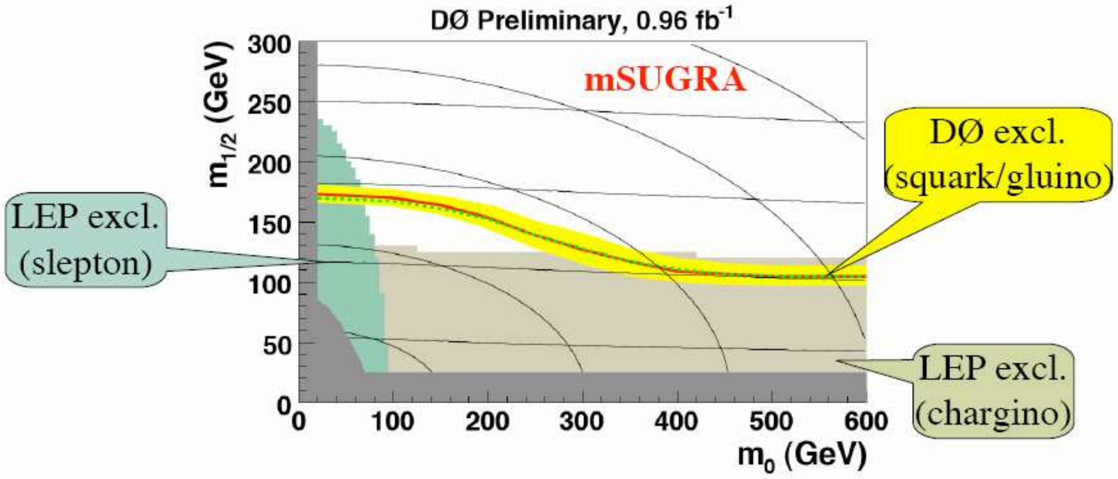
e+e- →$\chi_1\chi_2$

Kalinowski

Squarks and gluinos



M($\tilde{g}$)>290-410 GeV, M($\tilde{q}$)>375 GeV



- Nice interplay of hadron colliders and e⁺e⁻ colliders:
  - Similar sensitivity to same high level theory parameters via very different analyses
  - Tevatron is starting to probe beyond LEP in mSUGRA type models

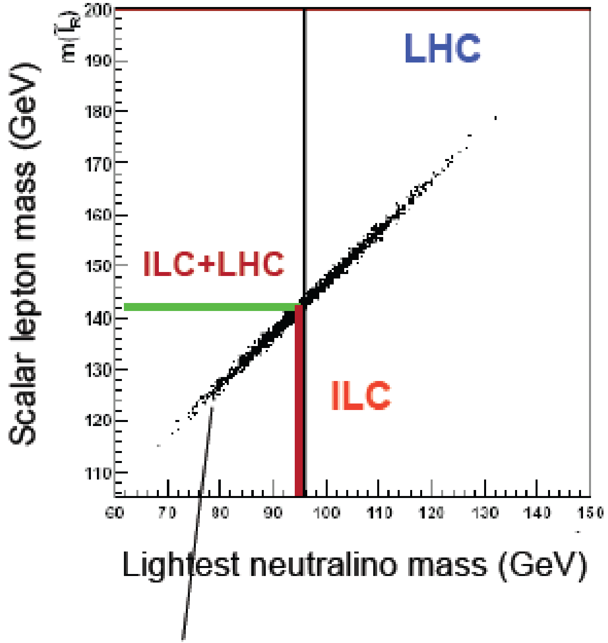
Using the M(χ^0_1) from ILC

300 fb^{-1}@LHC
ΔM values in GeV

	LHC	LHC+LC (0.2%)
$\Delta m_{\tilde{\chi}_1^0}$	4.8	0.19
$\Delta m_{\tilde{l}_R}$	4.8	0.34
$\Delta m_{\tilde{\chi}_2^0}$	4.7	0.24
$\Delta m_{\tilde{q}_L}$	8.7	4.9
$\Delta m_{\tilde{b}_1}$	13.2	10.5

(ILC input)

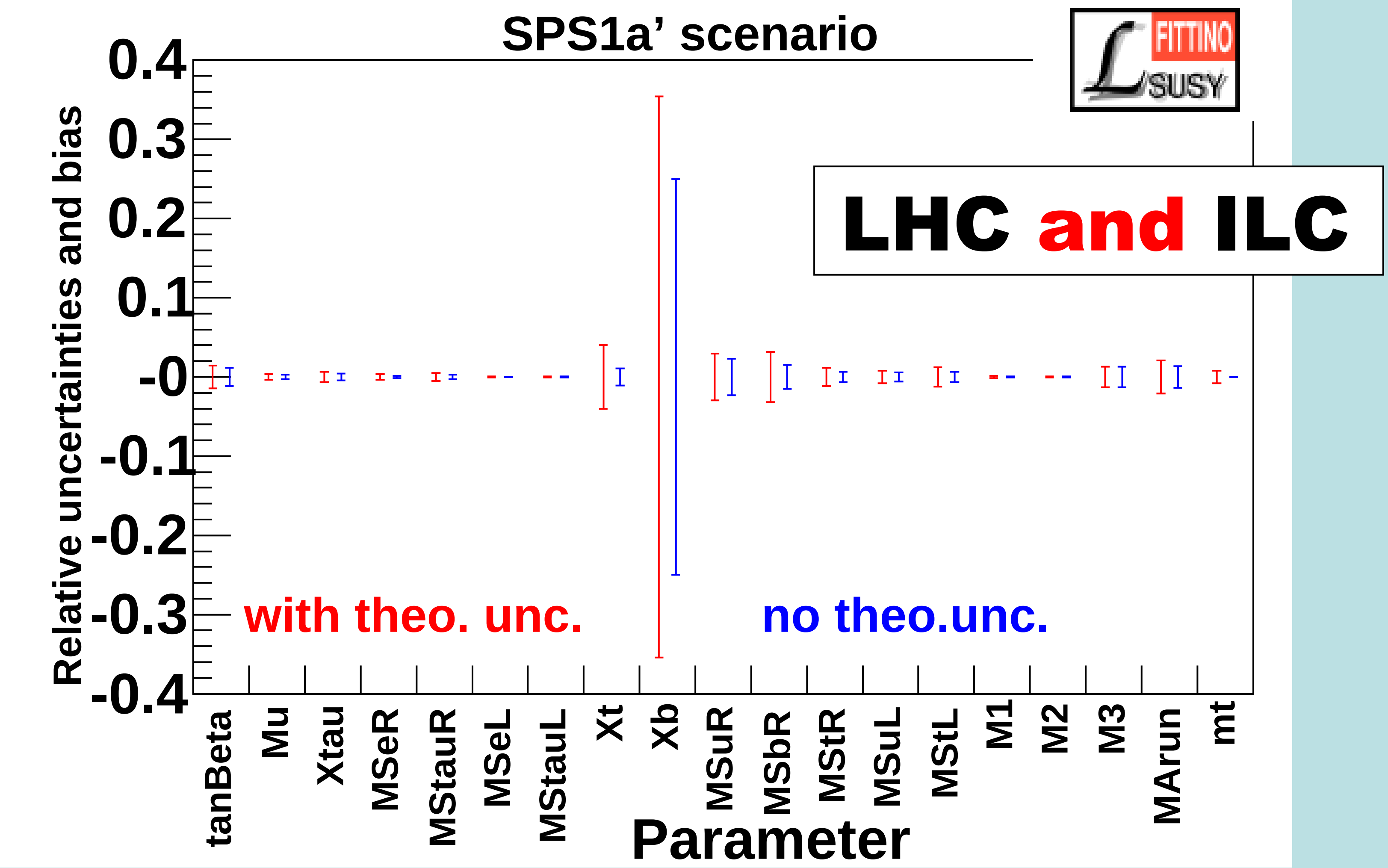
Significant improvements even if only m(χ^0) is measured at ILC



Strong correlation at LHC

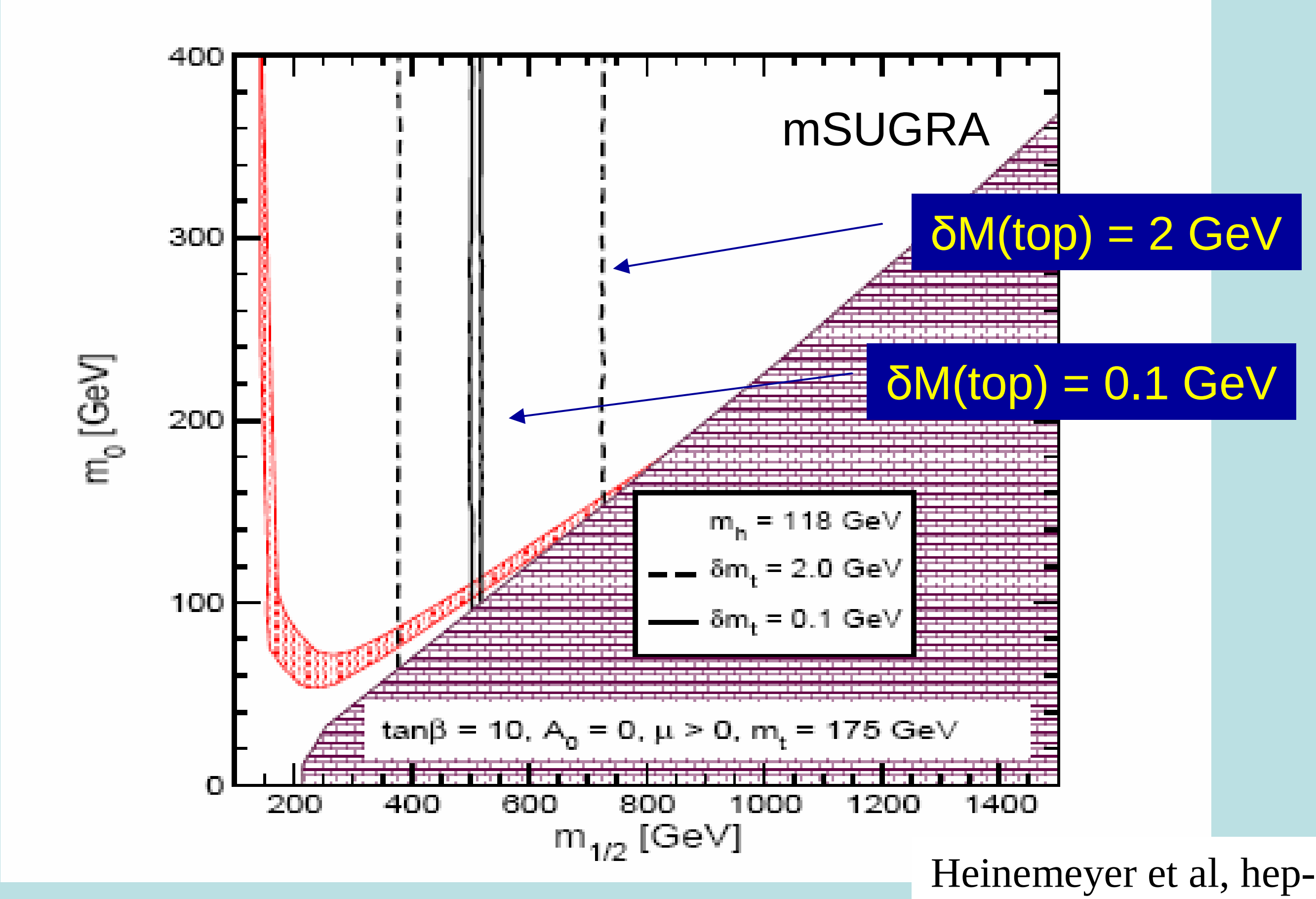
An input from ILC resolve this correlation

MSSM parameters from global fit



→ only possible with information from BOTH colliders

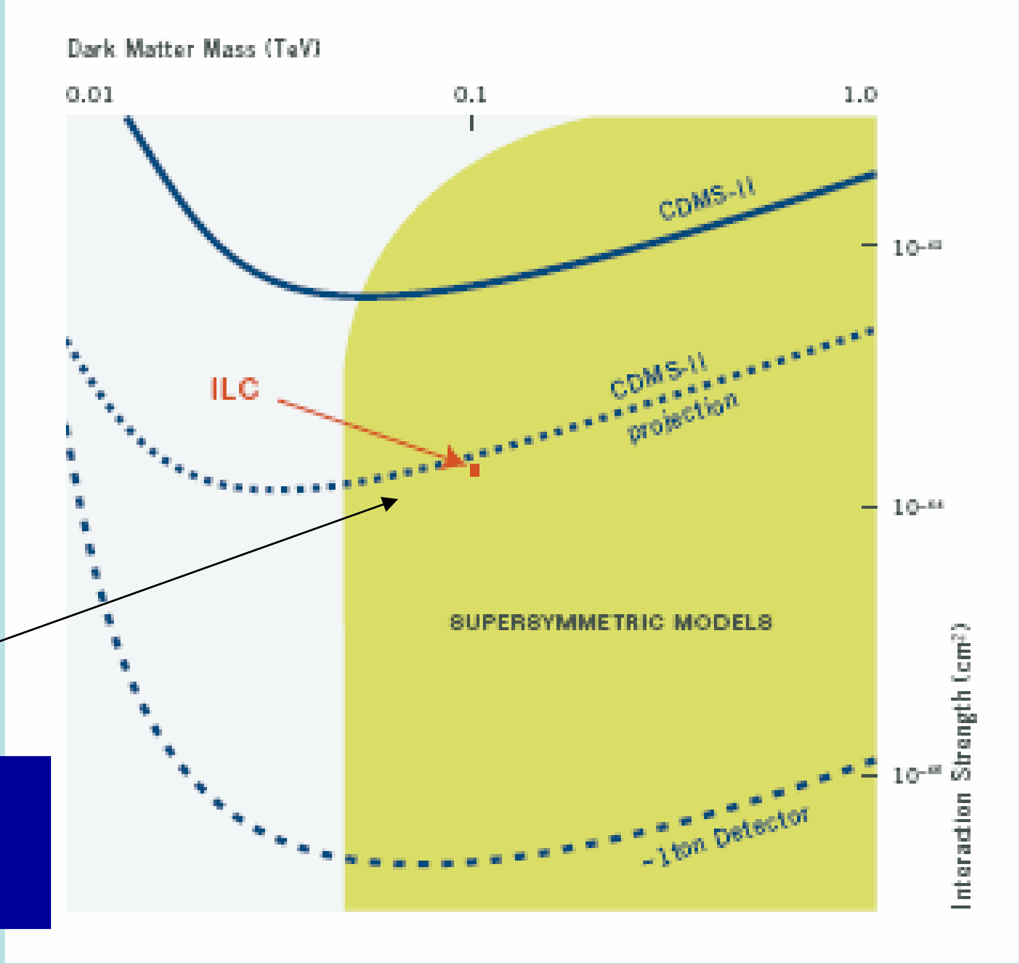
Precision electroweak tests



Heinemeyer et al, hep-ph/0306181

→ constrain allowed parameter space

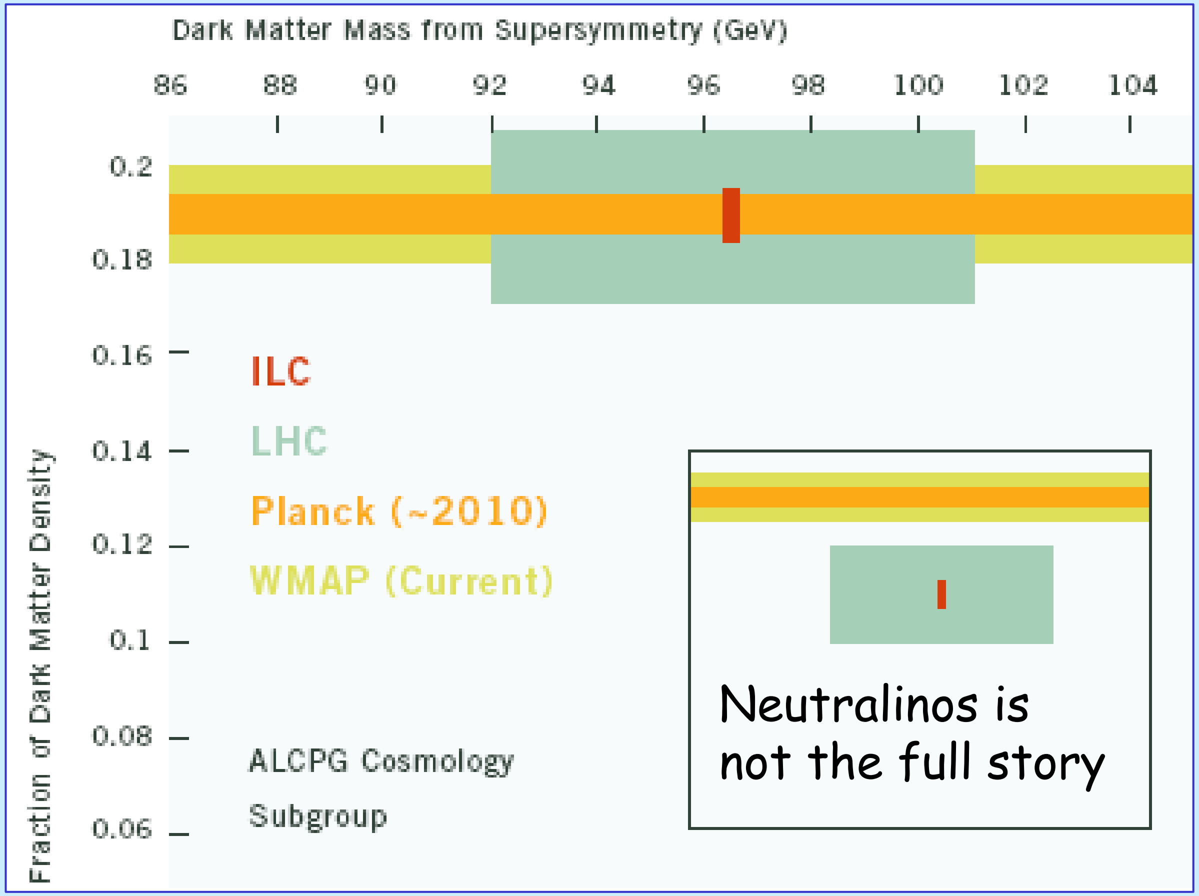
Comparison with expectations from direct searches



constrain mass and interaction strength

Dark Matter and SUSY

- Is dark matter linked to the Lightest Supersymmetric Particle?



Neutralinos is not the full story

ILC and satellite data (WMAP and Planck):

complementary views of dark matter.

ILC: identify DM particle, measures its mass;

WMAP/Planck: sensitive to total density of dark matter.

Together they establish the nature of dark matter.

LHC and LC results should allow,
together with dedicated dark matter searches,
first discoveries in the dark world

around 73% of the Universe is in some mysterious “dark energy”. It is evenly spread, as if it were an intrinsic property of space. It exerts negative pressure.

Challenge:
get first hints about the world of
dark energy in the laboratory

The Higgs is Different!

All the matter particles are spin-1/2 fermions.
All the force carriers are spin-1 bosons.

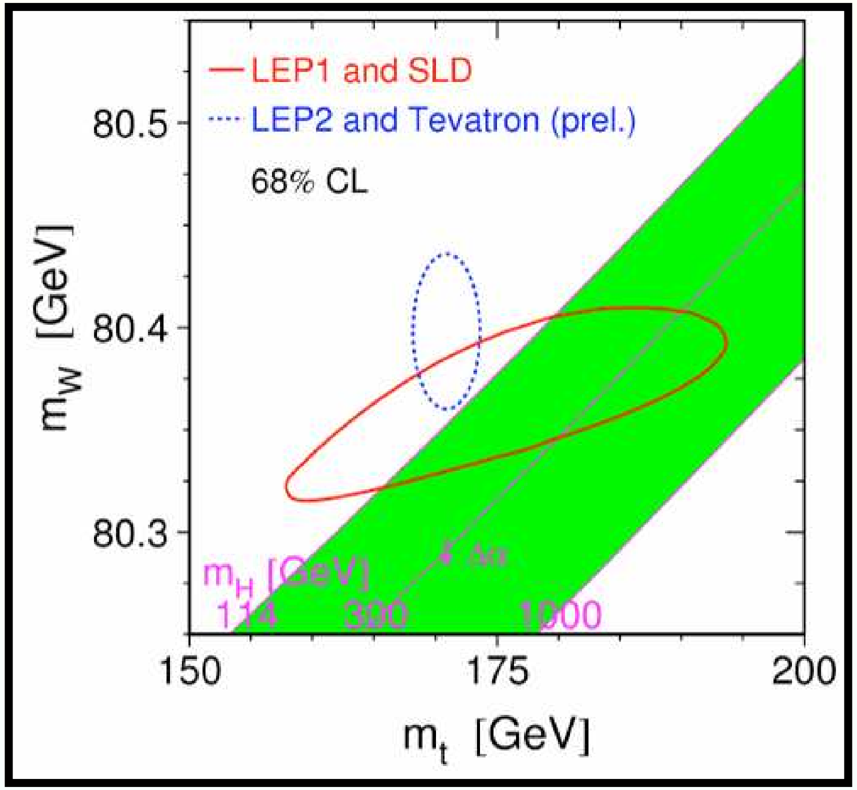
Higgs particles are spin-0 bosons.
The Higgs is neither matter nor force;
The Higgs is just different.
This would be the first fundamental scalar ever discovered.

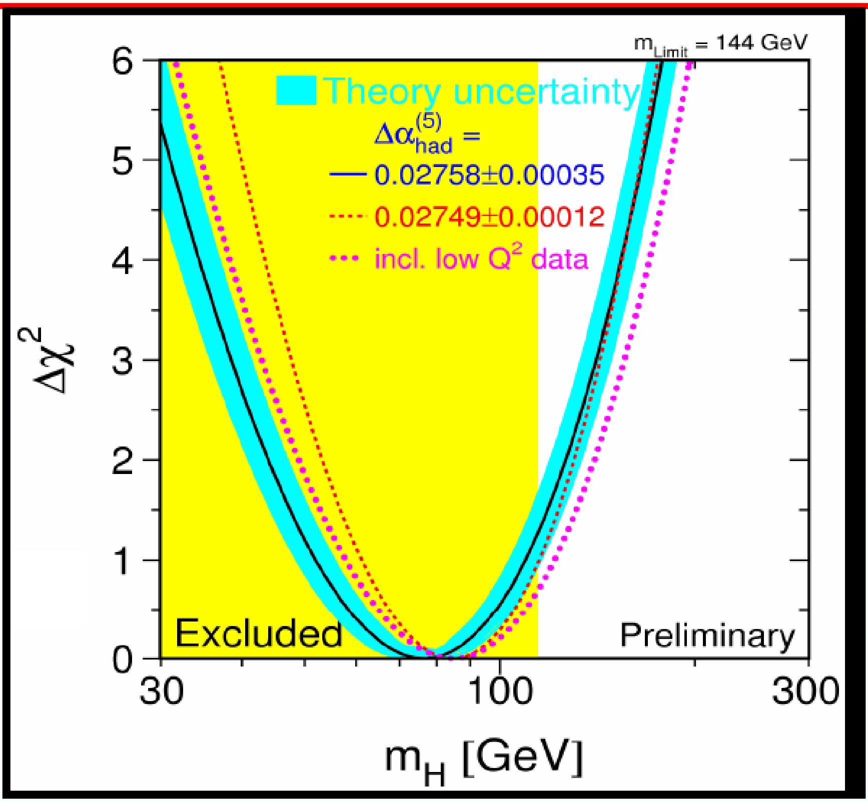
The Higgs field is thought to fill the entire universe.
Could give some handle of dark energy(scalar field)?

Many modern theories predict other scalar particles like the Higgs.
Why, after all, should the Higgs be the only one of its kind?

LHC and LC can search for new scalars with precision.

The SM bottom line





$M_H = 76^{+33}_{-24}$ GeV

Incl. theory uncertainty:

$M_H < 144$ GeV (95%CL)

Direct search limit (LEP-2):

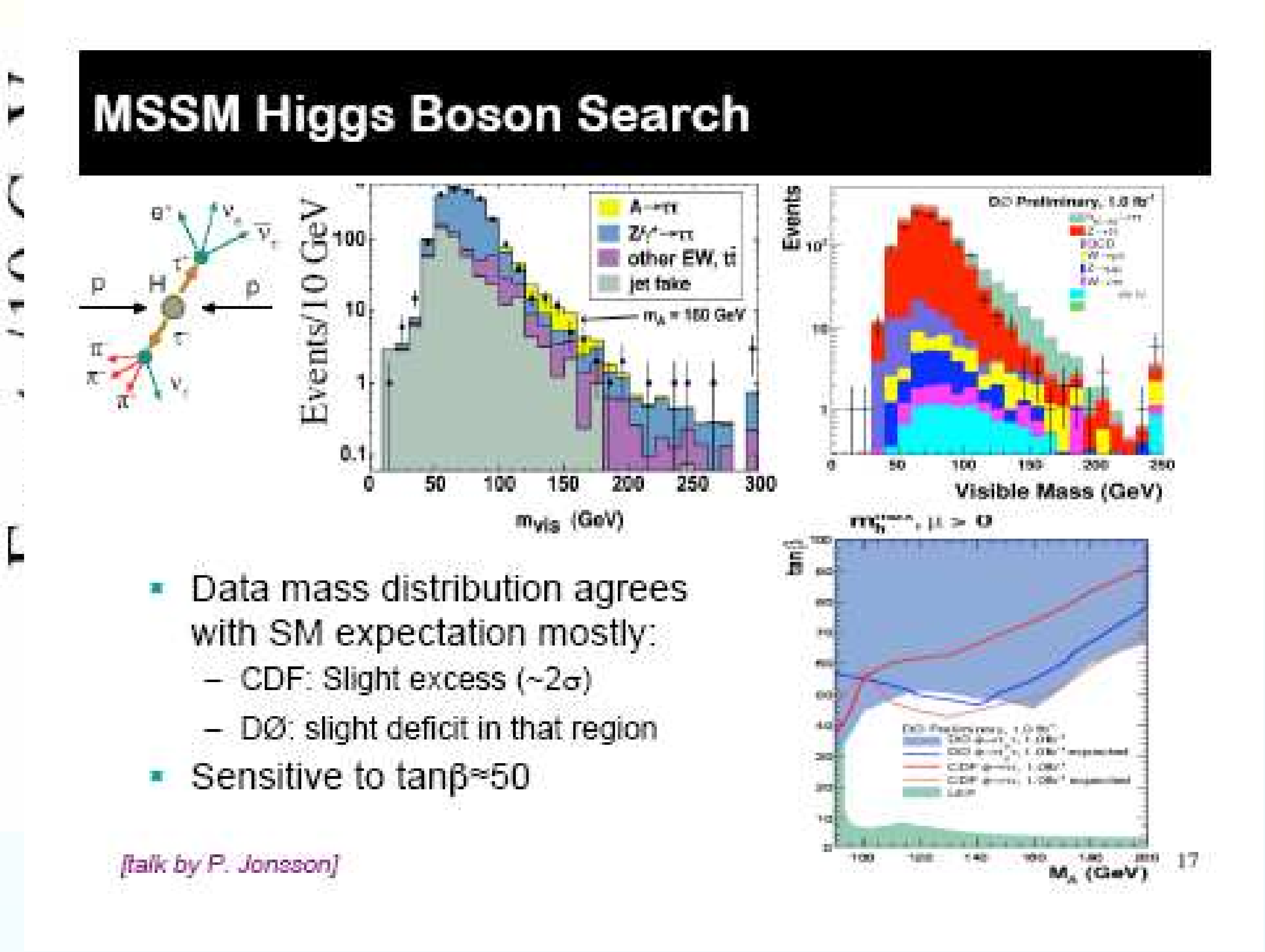
$M_H > 114$ GeV (95%CL)

Probability M_H>114 GeV: 15%

Renormalise probability for M_H>114 GeV to 100%:

$M_H < 182$ GeV (95%CL)

A hint of a MSSM Higgs?



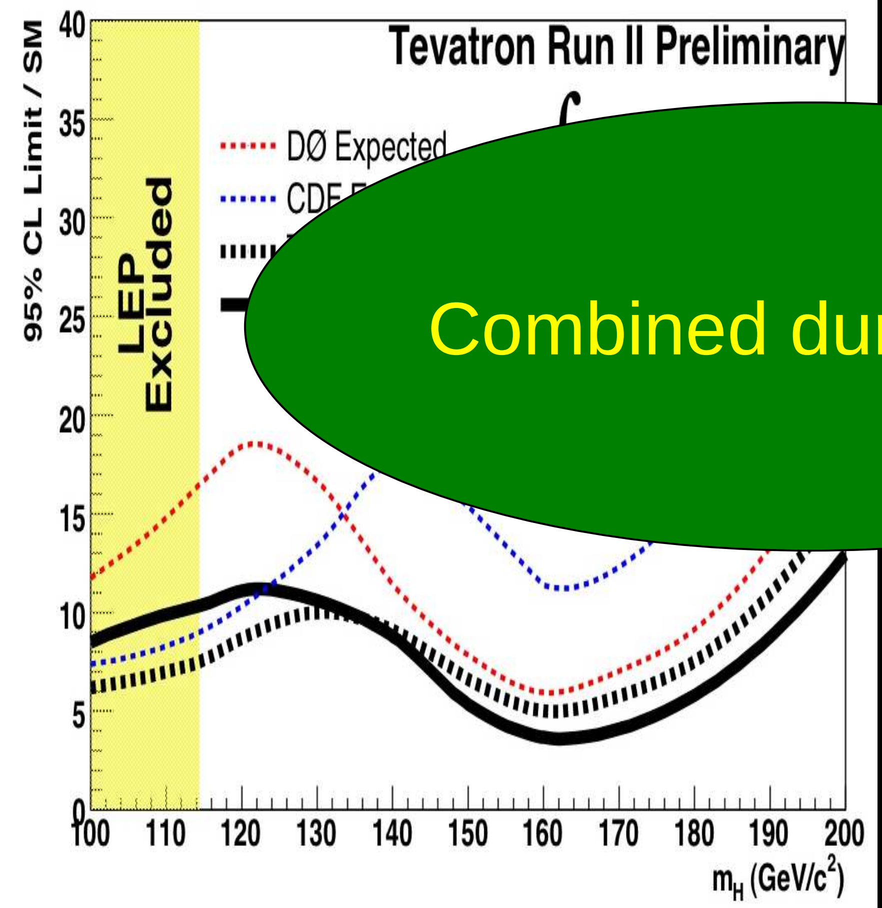
MSSM Higgs Boson Search

- Data mass distribution agrees with SM expectation mostly:
  - CDF: Slight excess (~2σ)
  - DØ: slight deficit in that region
- Sensitive to tanβ≈50

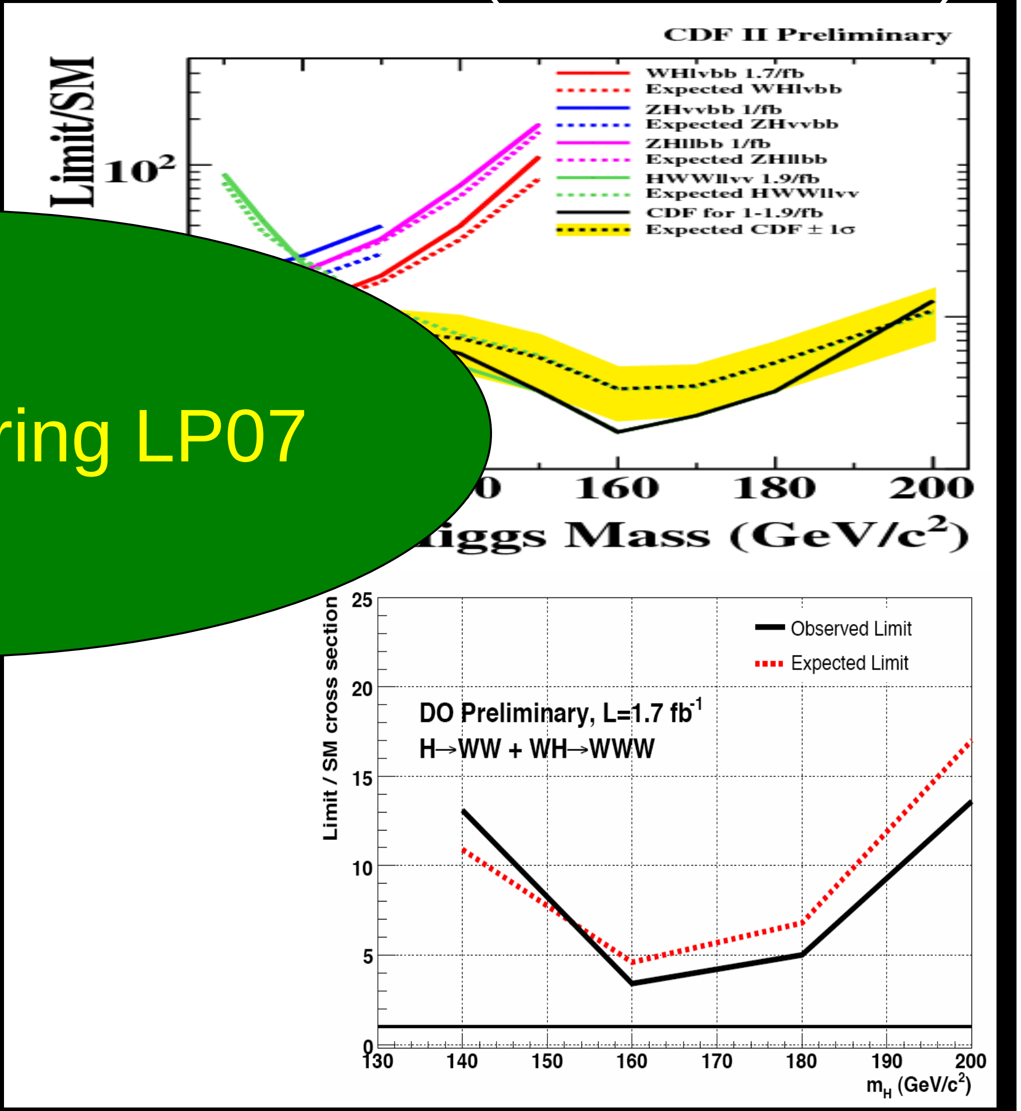
[talk by P. Jonsson]

SM Higgs Searches at Tevatron

Summer 2006



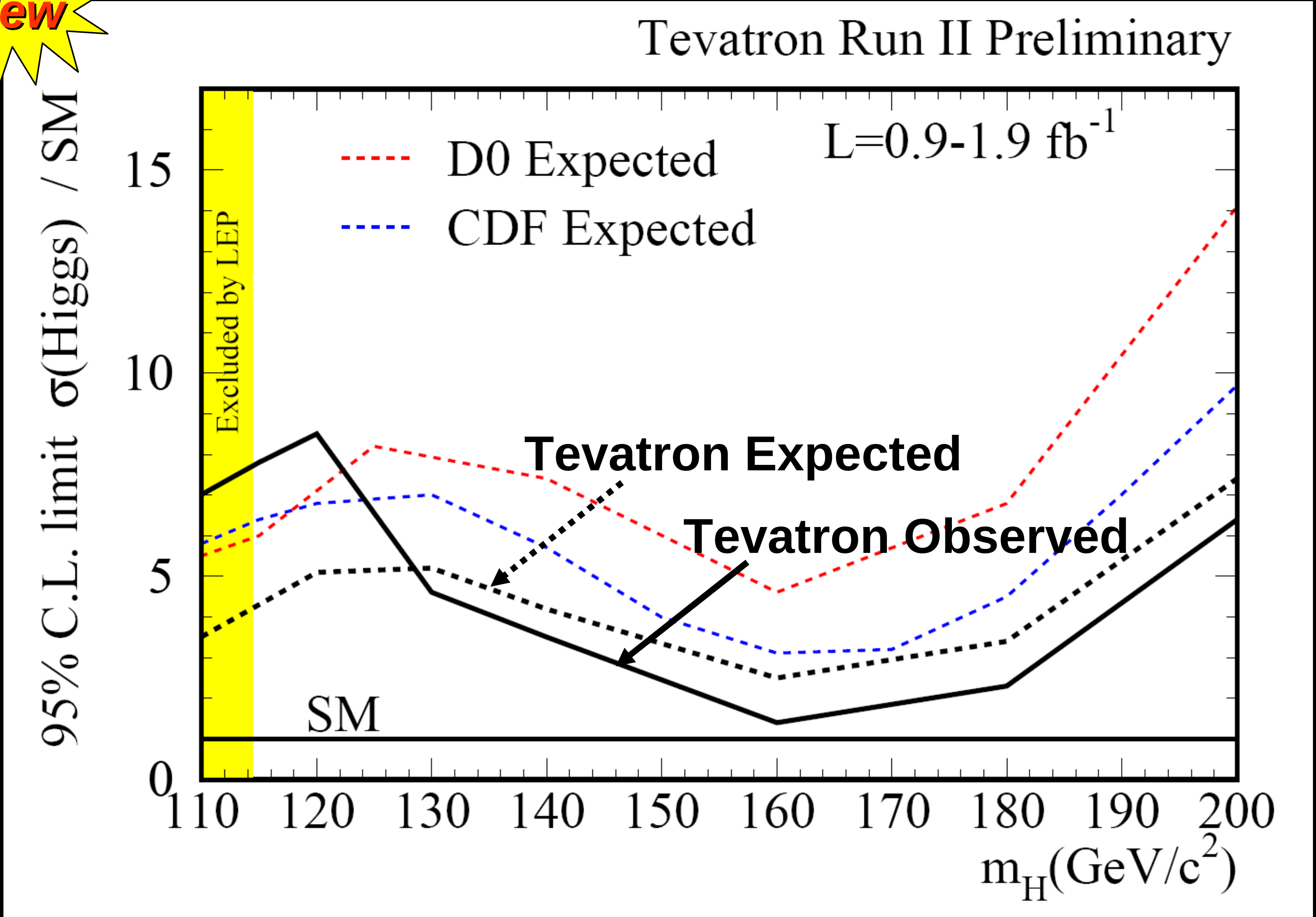
New in 2007 (to be combined)



Combined during LP07

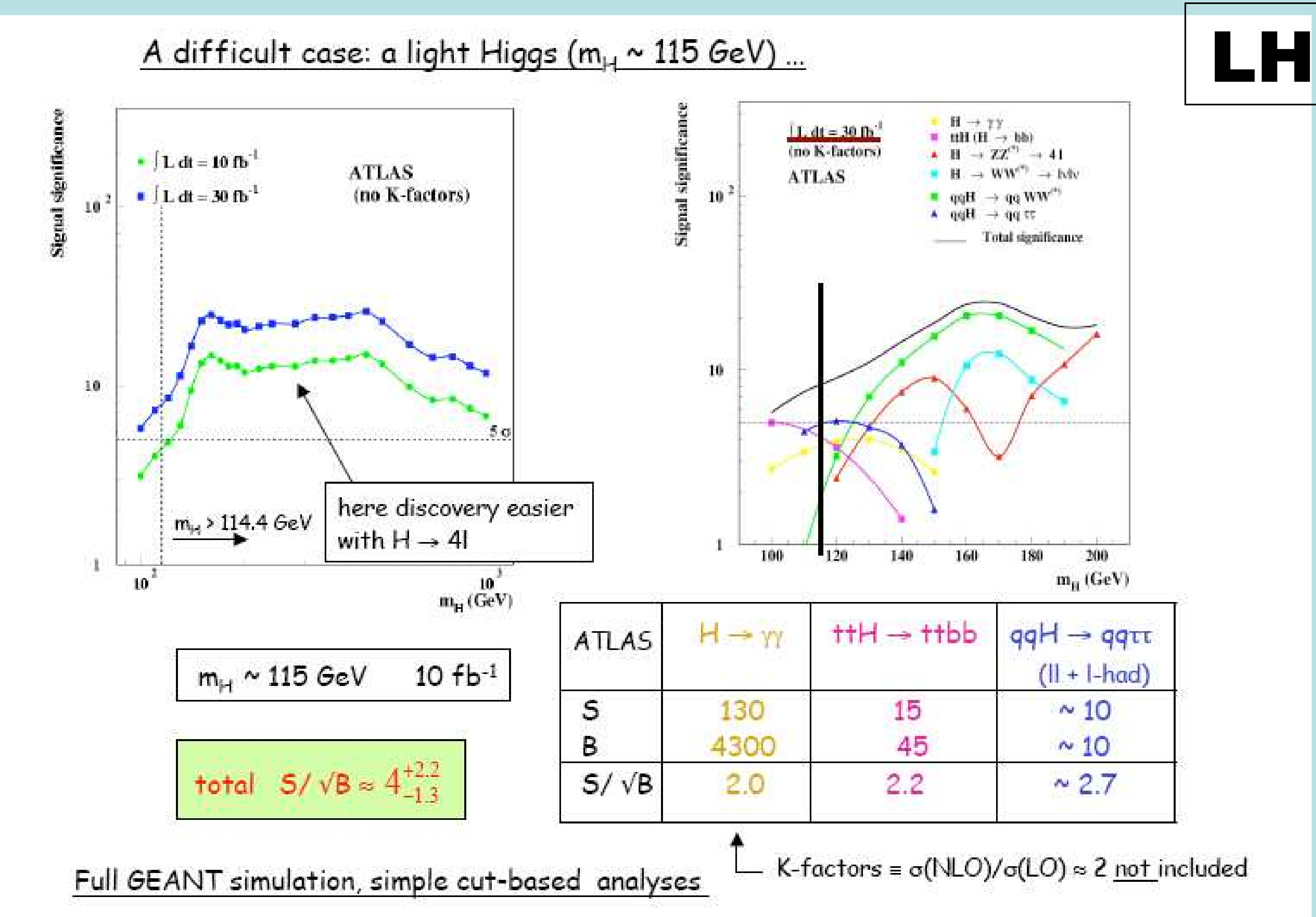
SM Higgs Searches at Tevatron

New



LHC

A difficult case: a light Higgs ($m_H \sim 115$ GeV) ...



here discovery easier with $H \rightarrow 4l$

$m_H \sim 115$ GeV   10 fb^{-1}

total $S/\sqrt{B} \approx 4^{+2.2}_{-1.3}$

ATLAS	$H \rightarrow \gamma\gamma$	$ttH \rightarrow ttbb$	$qqH \rightarrow qq\tau\tau$ (ll + l-had)
S	130	15	~ 10
B	4300	45	~ 10
$S/\sqrt{B}$	2.0	2.2	~ 2.7

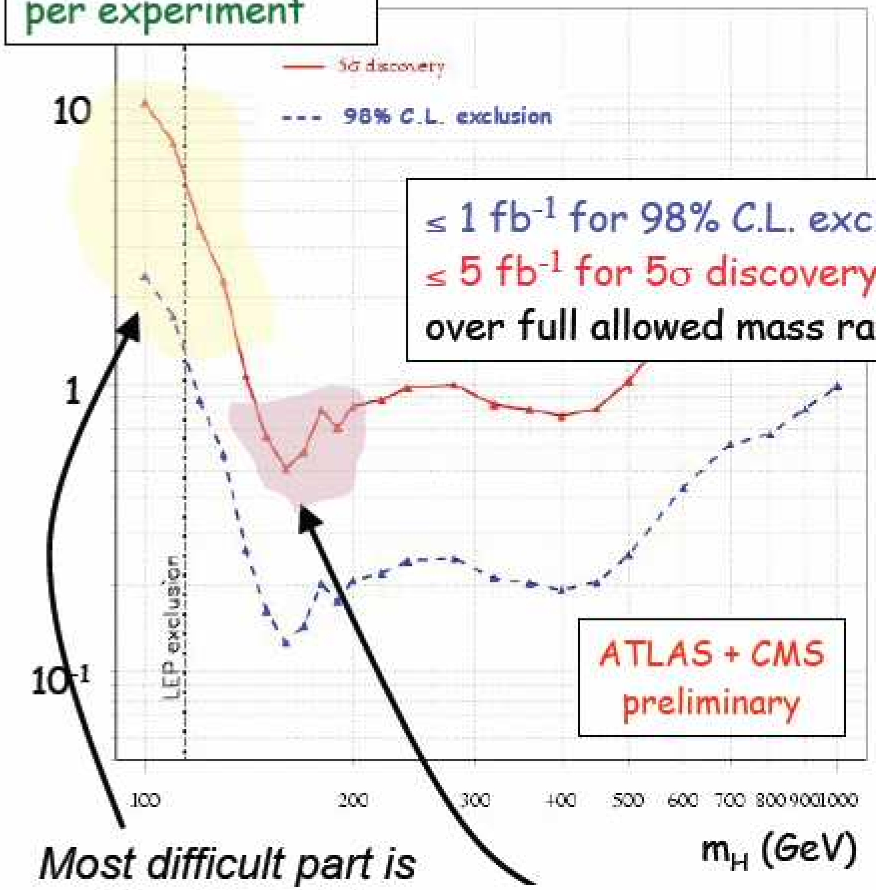
K-factors ≡ σ(NLO)/σ(LO) ≈ 2 not included

Full GEANT simulation, simple cut-based analyses

from F. Gianotti (LP05)

SM Higgs Reach

LHC



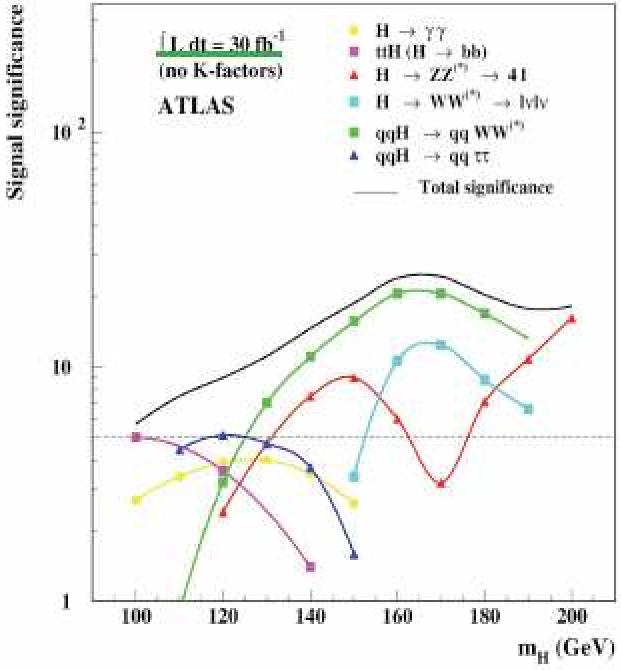
Needed ∫Ldt (fb^{-1}) per experiment

≤ 1 fb^{-1} for 98% C.L. exclusion
≤ 5 fb^{-1} for 5σ discovery
over full allowed mass range

ATLAS + CMS
preliminary

Most difficult part is M_h~115 GeV

Early discovery already Possible with $1fb^{-1}$ $H \rightarrow WW^{(*)} \rightarrow 2l$

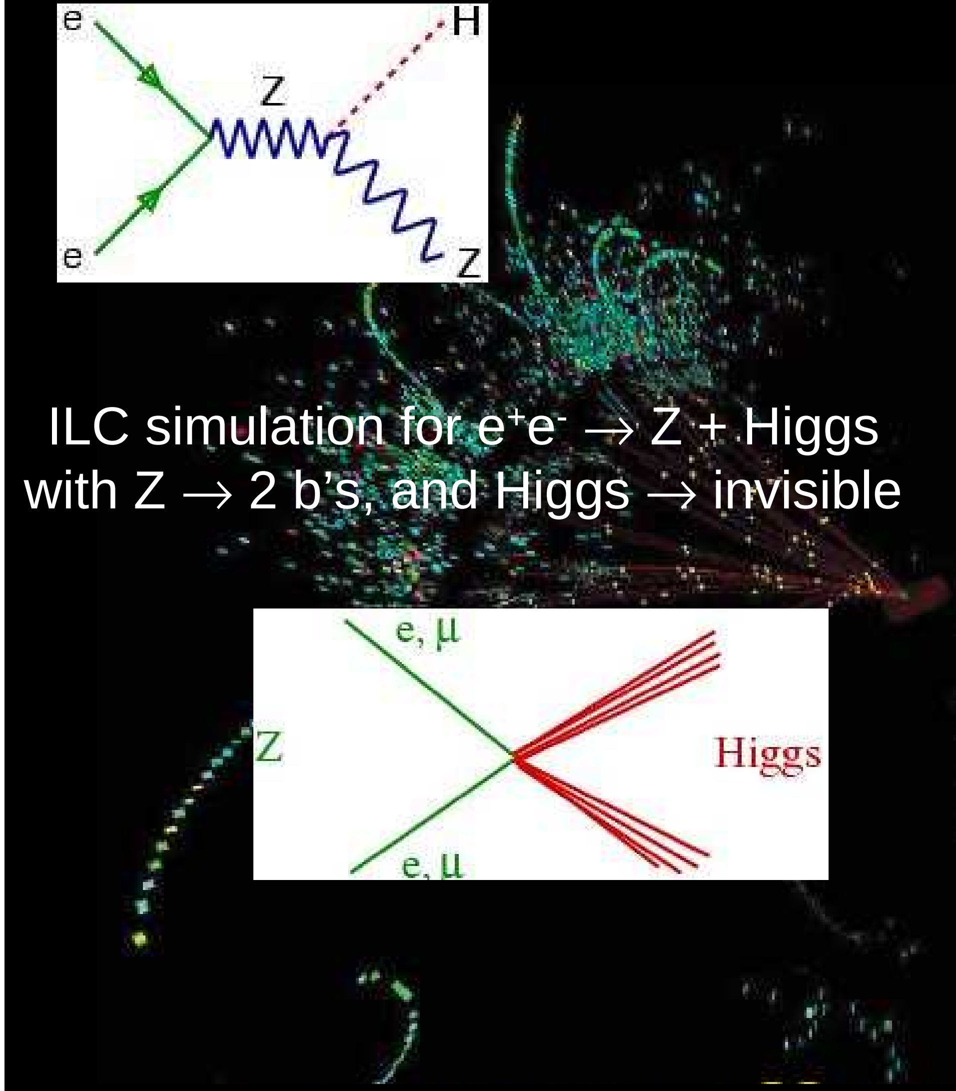


With $1fb^{-1}$ of understood data:

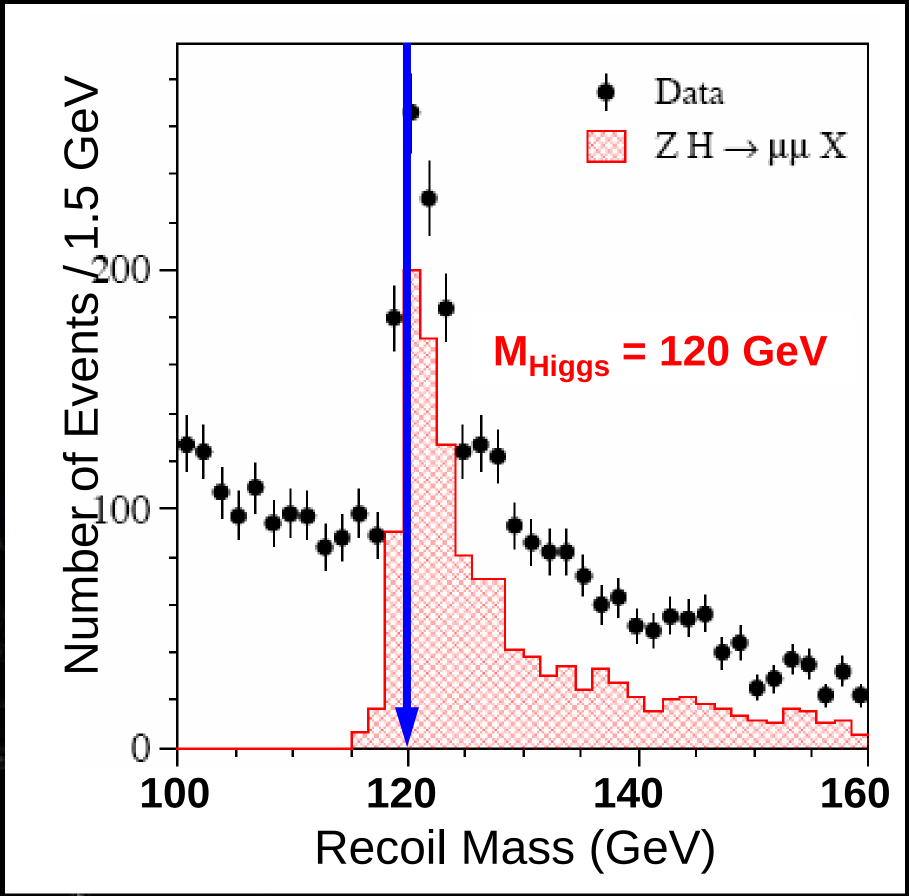
- *potential to exclude almost all m_h values*
- *potential to discover higgs with m_h~165 GeV*

LHC will give us an answer!

LC can observe Higgs no matter how it decays!

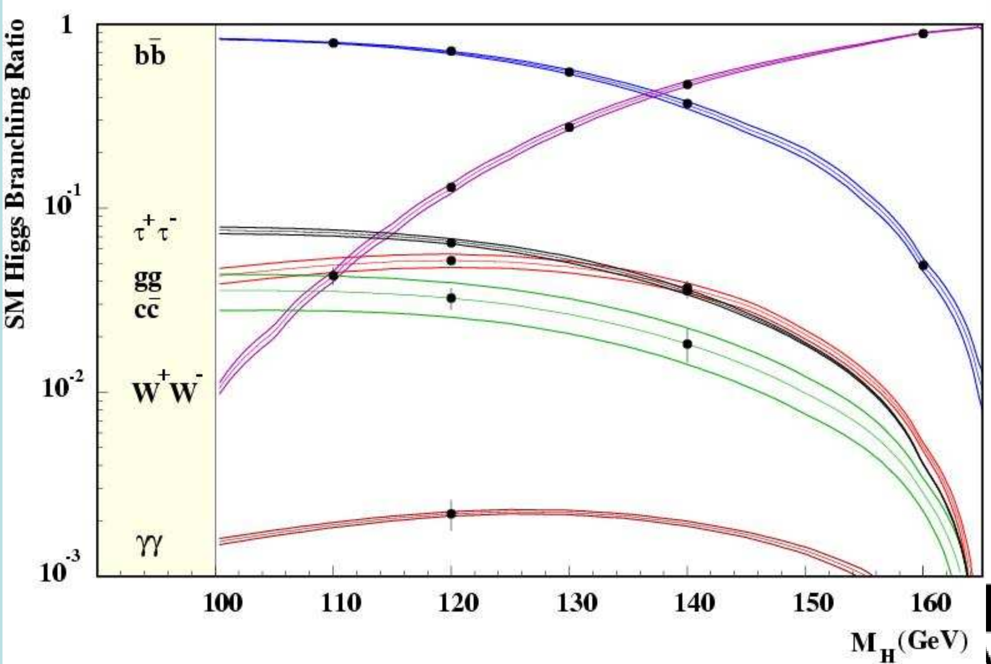


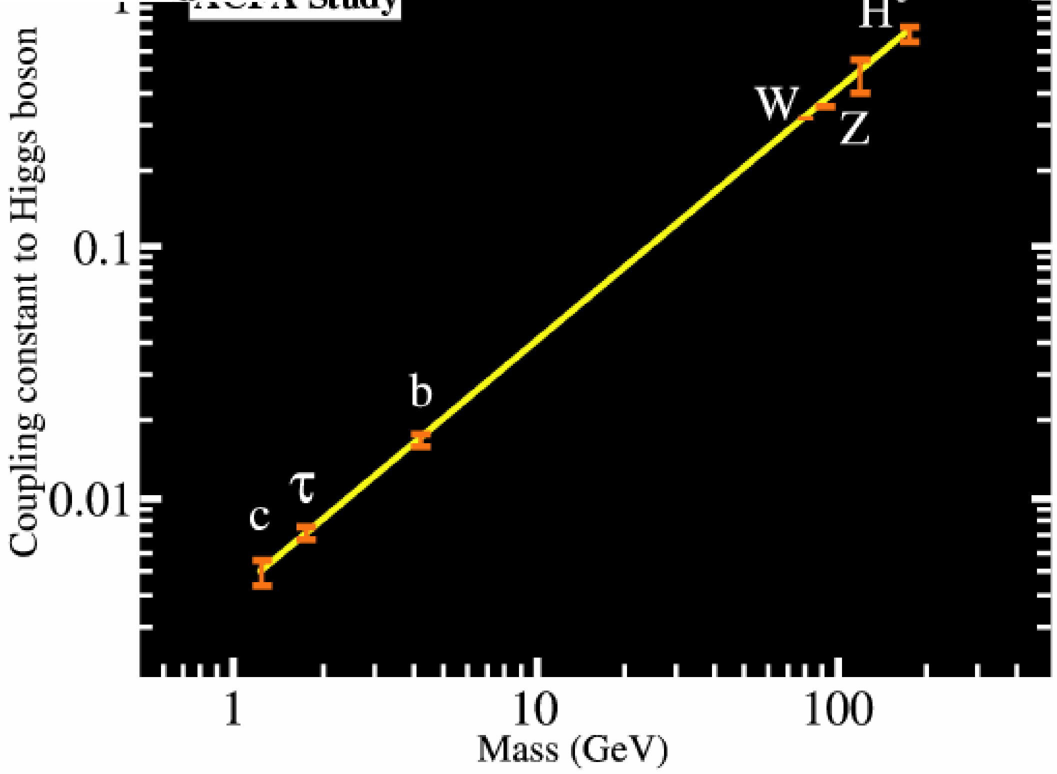
ILC simulation for $e^+e^- \to Z$ + Higgs with $Z \to 2$ b's, and Higgs → invisible



Only possible at the LC

Precision Higgs physics

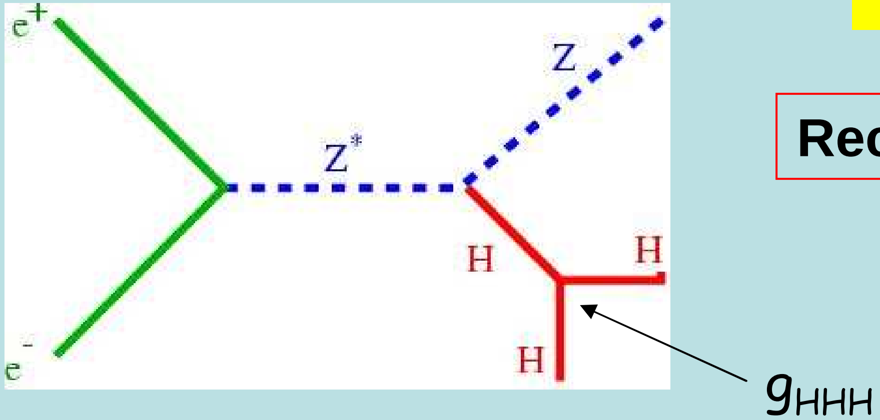


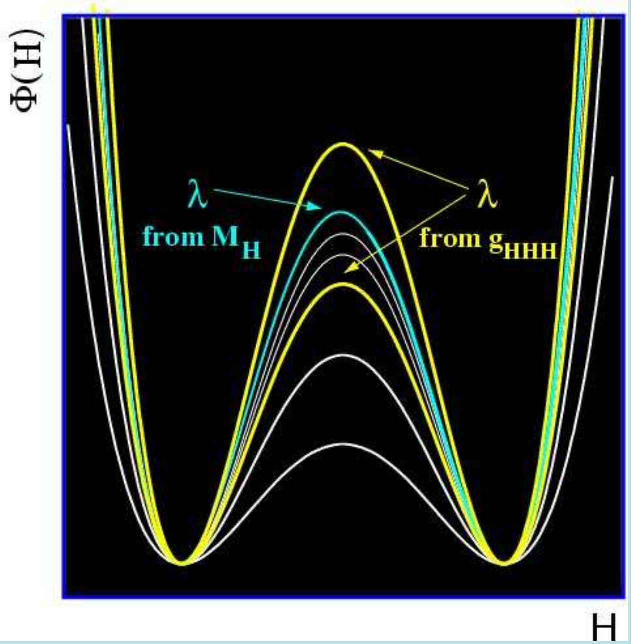


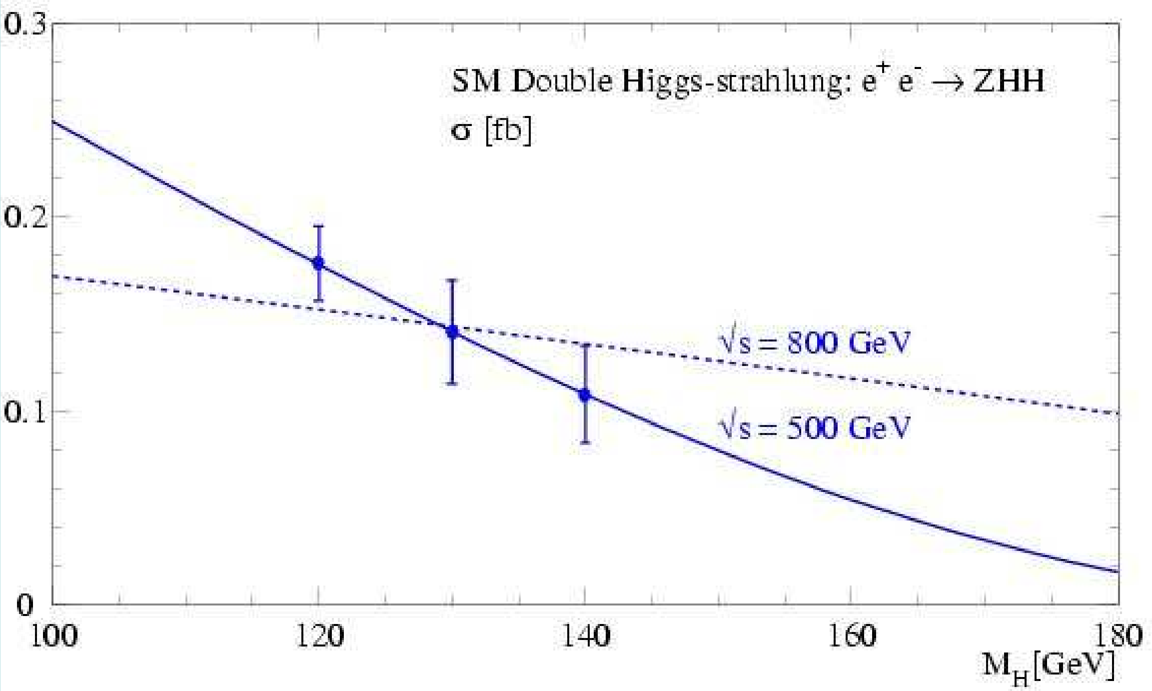
Determination of absolute coupling values with high precision

Precision Higgs physics

Reconstruction of the Higgs potential







$\Delta\lambda/\lambda$ ~ 10-20 %
for 1 ab^{-1}

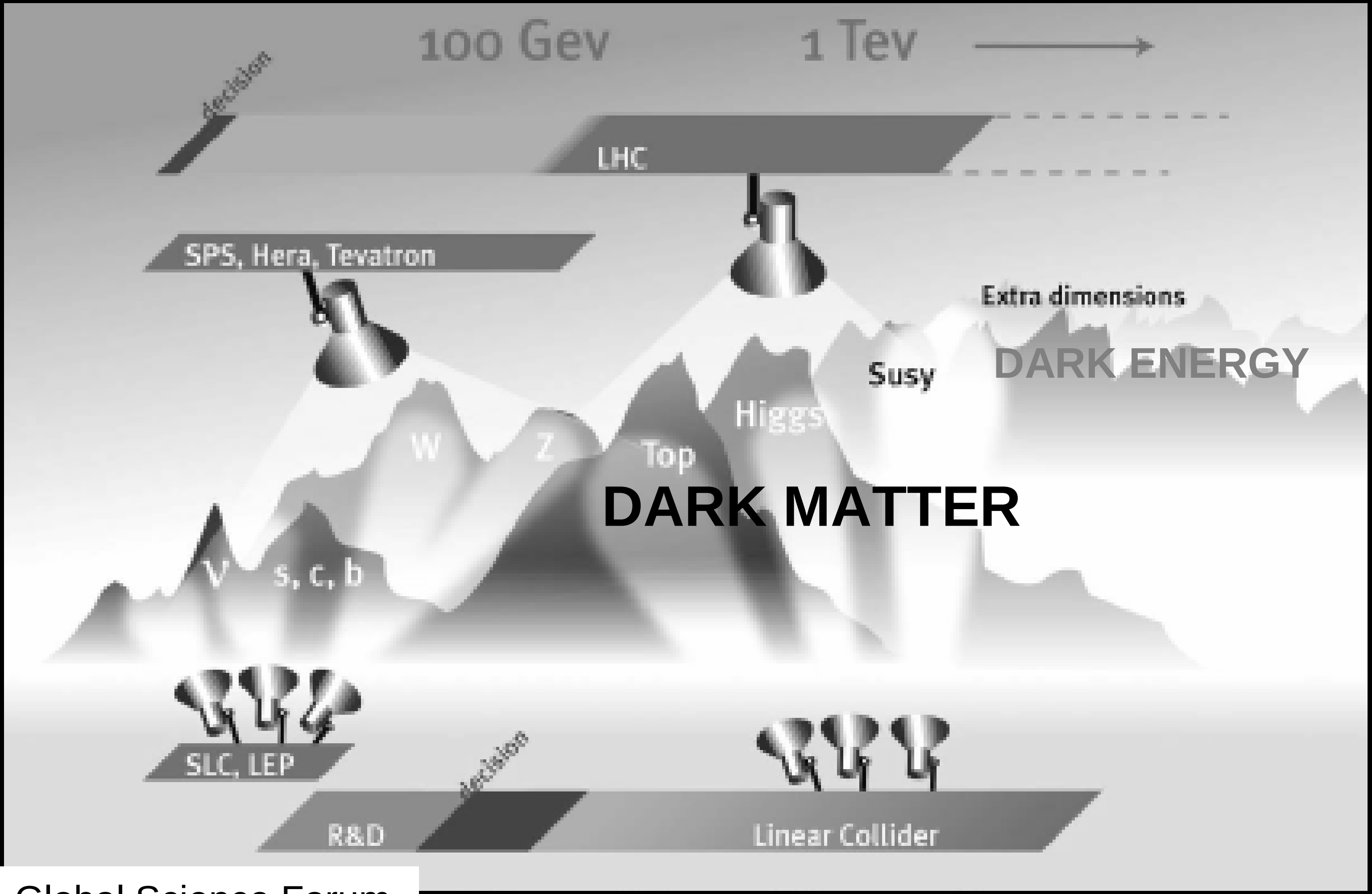
Only possible at LC

LHC and (I)LC results will allow
to study the Higgs mechanism in detail and
to reveal the character of the Higgs boson

This would be the first investigation
of a scalar field

This could be the very first step to
understanding dark energy

LHC and LC *together* will allow first discoveries in the dark world



from Global Science Forum

Past decades saw precision studies of 5 % of our Universe → Discovery of the Standard Model

The LHC will soon deliver data

Preparations for the ILC as a global project are under way

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the future is bright in the dark world

and will hopefully have some relaxing moments in the mountains